

**EXPERIMENTAL VERIFICATION OF A**  
**HIGH VELOCITY PROJECTILE**  
**IMPACT MODEL FOR**  
**COMMERCIAL EXPLOSIVES**

**\*\* FINAL REPORT \*\***

**VOLUME 1**

**BY**

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**SUPERVISOR: DR. A. BAUER**

Work on this project was conducted under the auspices of the  
Canada Centre for Mineral and Energy Technology, Energy, Mines  
and Resources, Canada.

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CANMET Scientific Authority: Dr. K.K. Feng**

**MINING RESOURCE ENGINEERING LIMITED  
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### SUMMARY

The phenomenon of high velocity impact initiation of commercial explosives was modelled numerically by means of a reactive hydrodynamic code in conjunction with the Forest Fire model. Coefficients for the Forest Fire model were determined from the Pop plots resulting from a series of wedge tests for each explosive investigated. Data for the reactive hydrodynamic code include the HOM equation of state parameters and Hugoniot.

Predicted results for projectile impact were compared with the experimental results obtained for the same explosive compositions. For a given projectile the agreement between the predicted values of impact velocity beyond which detonation would occur and the observed experimental values was good.

RESUME

Le phénomène du déclenchement à l'impact ultra-rapide des explosifs commerciaux fut développé numériquement par l'entremise d'un code hydrodynamique réactif conjointement avec le modèle Forest Fire. On a établi les coefficients du modèle Forest Fire des graphiques Pop dérivés d'une suite de "Wedge Tests" effectués pour chaque explosif étudié. Les données du code hydrodynamique réactif inclut l'équation HOM des paramètres d'état et des valeurs Hugoniots.

On a comparé les résultats conjecturés de l'impact de projectile aux résultats expérimentaux obtenus pour les mêmes mélanges explosifs. Pour un projectile donné l'accord était bon entre les valeurs prédites de la vitesse d'impact au-dessus de laquelle la détonation se produirait et les valeurs expérimentaux observées.



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## CHAPTER ONE

### 1.0 INTRODUCTION

Explosives may be initiated by shock, burning or friction. Whatever the method of delivering energy to the explosive, the initiation process always passes through a stage where shock creation is the most important feature. The most natural sequence of events, very common in accidents related to explosives is shown in Figure 1. The chain or sequence of events leading to detonation can be entered at any point. High velocity impact sensitivity is however related to the last parts of the chain, that is the shock to detonation transition where the explosive is initiated by a shock wave. The shock to detonation transition will be studied in detail in the following.

With regard to the initiation process explosives can be differentiated into two main categories; homogeneous and heterogeneous explosives. Homogeneous explosives are those explosives which do not contain any discontinuities in their mass. Heterogeneous explosives are those explosives in which discontinuities such as gas bubbles, grit, solid metallic or non metallic particles and air bubbles are present in their mass. The method of initiation is different between the two categories. If one introduces gas bubbles or grit into a homogenous explosive, the minimum shock pressure necessary for initiation of detonation can be decreased by about one order of magnitude.

According to Campbell, Davis and Travis<sup>(4)</sup> when a homogeneous explosive is shocked, the detonation starts at the interface between the donor and the acceptor charge (Figure 2). Their experiments involved the shocking of nitromethane with plane waves. Plane wave lenses were combined with boosters and inert shock attenuator plates to produce a shock wave of the desired amplitude in the test explosive. The behaviour of the

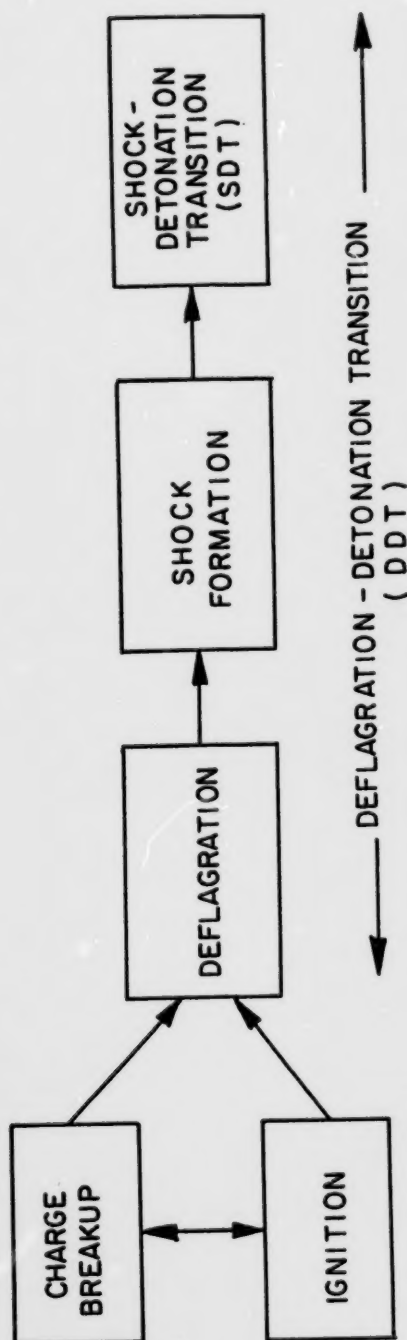


FIGURE 1: SEQUENCE OF EVENTS LEADING TO A DETONATION

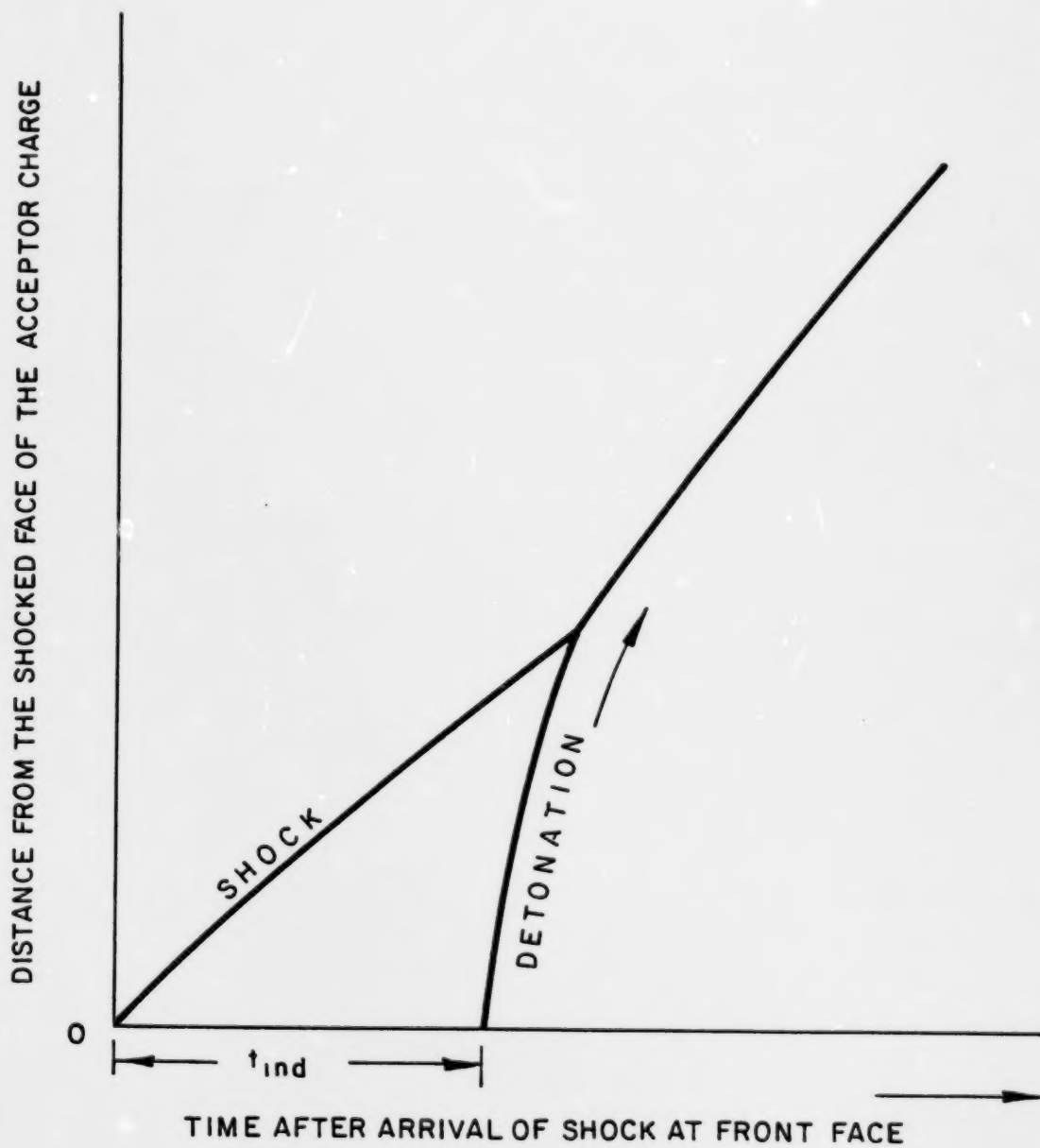


FIGURE 2: SHOCK TO DETONATION TRANSITION IN HOMOGENEOUS EXPLOSIVES

test explosive was observed before the intrusion of edge effects or reverberations in the attenuator. The shock wave would compress the nitromethane and at the same time heat it. The shock heated explosive reacts slowly at first but the reaction rate accelerates due to exothermic decomposition of the nitromethane. Finally detonation results at the interface.

The same investigators have shown<sup>(5)</sup> that in non homogeneous explosives because of the discontinuities within composition the shock wave is rough. The flow is irregular in its fine detail. Because of the non homogeneous nature of the explosive local convergences occur. Reaction takes place in these small regions of convergence which are distributed throughout the explosive. The initiation of the explosive thus depends on the type, number and distribution of the inhomogeneities which cause shock interactions and local shock concentrations.

By using photographic techniques it has been found that when the shock wave enters the explosive it proceeds at a slowly increasing velocity for a distance which is a function of the shock pressure. Eventually the shock velocity increases to a value associated with high order detonation. A qualitative explanation of the experimental results would be as follows. The shock wave interacts with density discontinuities to produce local concentrations of energy, the "hot spots". The hot spots decompose and liberate energy which strengthens the shock so that when it interacts with additional inhomogeneities, the interaction is more intense and higher temperature hot spots are formed. This results in a larger mass fraction of the explosive being decomposed in the shock. Thus the shock wave grows stronger and stronger releasing more and more energy until it becomes strong enough for a high enough percentage of the explosive to react in the shock wave and detonation occurs. A typical distance from the impacted surface - time record for the case of non homogeneous explosives is shown in Figure 3.

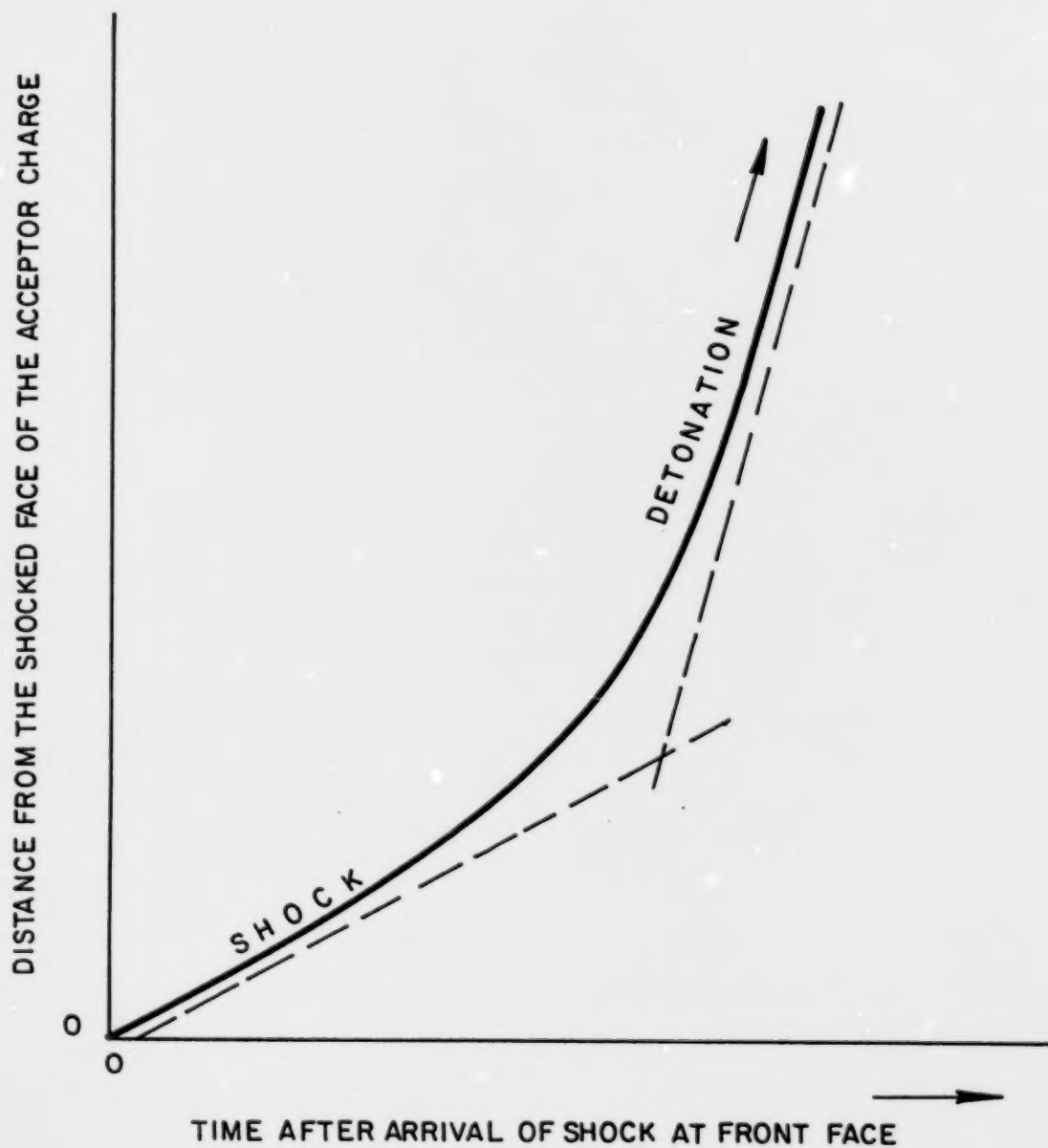


FIGURE 3: SHOCK TO DETONATION TRANSITION IN HETEROGENEOUS EXPLOSIVES

The main differences between the behaviour of homogeneous and heterogeneous explosives with regard to their impact initiation are the following:

- a. The initial shock wave in a homogeneous explosive shows a constant or slightly decaying velocity as a function of time; the corresponding wave in heterogeneous explosives accelerates throughout its travel.
- b. The transition to high-order detonation is very abrupt in homogeneous explosives; the transition in heterogeneous explosives is gradual.
- c. Detonation is observed to originate at the impacted surface in homogeneous explosives; detonation occurs inside the explosive in the case of heterogeneous explosives.
- d. Heterogeneous explosives are much more sensitive than homogeneous explosives.

Since commercial explosives are heterogeneous products the focus of this study will be on heterogeneous explosives.

### 1.1 THE HOT SPOT CONCEPT

The formation within the explosive of hot spots having temperatures greatly exceeding that of the rest of the explosive was originally proposed by Bowden and Yoffee.<sup>(3)</sup> According to them when a solid explosive is subjected to impact or friction, the explosion which may result is generally thermal in origin. This means that the mechanical energy must first be degraded to heat and concentrated in small localized regions to form "hot spots". It was found that there are three classes of hot spots.



- a. Voids within the explosive (bubbles).
- b. Regions where the explosive is heated by viscous flow or plastic deformation when rapidly flowing explosive escapes from between impacting surfaces.
- c. Points of friction at the surface of container walls, on grit particles or between crystals of explosive.

In recent years it has been found that the voids inside the explosive are of paramount importance to its sensitivity. The theory proposed initially was that the gas bubbles in the explosive would heat adiabatically to a sufficiently high temperature such that rapid decomposition of the explosive would start. However, the heat transfer between the bubble and the explosive is relatively slow for the duration of interest (a few microseconds). It appears that the adiabatic heating of the bubbles is very important for explosive initiation when the duration of the phenomenon is relatively long e.g. for the low velocity impact initiation of detonation. In the case of shock initiation adiabatic heating will contribute to the initiation but may not be the only mechanism leading to detonation.

To this end several other theories have been proposed.

Ljundberg<sup>(15)</sup> showed that the compression of spherical bubbles does not take place symmetrically. There is always a pressure gradient when a shock wave compresses a bubble. As a result of this and the inherent instability of an imploding concave surface, surface breakup occurs. Surface breakup increases the surface area and certainly improves burning if burning has already started. In this connection the following phenomena have to be considered:

- Adiabatic heating and cooling of the droplets due to the energy equivalent to the increase in surface.

- Cooling of the air of the droplets by heat transfer. If the total mass and surface area of the droplets is too great compared to the mass of the air the cooling effect may prevent ignition. However, if the mass of the droplets is too small, their combustion will not be sufficient to ignite the explosive. Moreover, when a plane shock wave front reaches a cavity, the material surrounding the cavity is given a velocity which is initially perpendicular to the nearest part of the bubble surface. The part of the bubble first reached by the shock, bulges inward and is further accelerated by the inflowing surrounding material so that a high velocity jet is generated. The jet on impact with the explosive can generate very high pressures. It appears that the jet effect could be responsible for the initiation in cases where a high strength shock is involved.

The hydrodynamic hot spot is the latest addition to the list of the possible mechanisms creating hot spots. It was introduced by Mader<sup>(19)</sup>. According to Mader the shock wave interacts with discontinuities (voids, particles etc.) and the resulting convergence of shock creates spots of high pressure and temperatures. These spots explode, thereby liberating energy which strengthens the shock which interacts with additional inhomogeneities creating more hot spots until finally the explosive decomposes.

Mader modelled the creation of the hot spot by using two dimensional hydrodynamics to study theoretically the formation of hot spots from shocks interacting with spherical, cylindrical or biconical voids and with cylinders and spheres of aluminum. However this modelling was idealized. It covered only cases where some well known inhomogeneities had been introduced in a homogeneous mass. Obviously such modelling is not possible in an actual situation where a variety of conditions will appear.

From the above it follows that although there is general acceptance of the hot spot concept, the exact function of the hot spot is not exactly understood. Due to the number of possible hot spots types, the relation of hot spot size and temperature to such parameters as void size, particle size and porosity is unknown, quantitatively at least.

## CHAPTER TWO

### MODELLING OF THE SHOCK INITIATION OF NON HOMOGENEOUS EXPLOSIVES - LITERATURE REVIEW

#### 1.0 INTRODUCTION

Although the exact mechanism of the generation of hot spots is not exactly known modelling of the shock initiation of explosives started as early as 1940 based on the hot spot concept and applying simplifying assumptions and empirical data. The use of Eyring's burning laws<sup>(9)</sup> were the first attempts to model hot spot initiation of explosives. According to the Eyring<sup>(9)</sup> and Cook<sup>(6)</sup> the explosive is reacted or burnt starting at the hot spot surface. In the case of solid granular explosives the burning starts at the surface of the grains and proceeds radially inward. In the case of liquid explosives containing bubbles Cook and Bauer<sup>(7)</sup> introduced a burning law according to which burning starts at the surface of the bubbles in the mass of the explosive and proceeds outwards. These laws in conjunction with the geometrical detonation head model and Arrhenius kinetics could explain the shape of the velocity of detonation - diameter curves in granular and liquid explosives. Moreover once the critical diameter and the ideal detonation velocity were known these models could reproduce the velocity diameter curves with sufficient accuracy considering the crudeness of their assumptions. The effect of applied pressure could also be explained in semi quantitative manner. These approaches however could not be used to predict the required conditions for the onset of detonation in an explosive.

Hubbard and Johnson<sup>(17)</sup> pioneered the use of one dimensional hydrodynamic computer codes to model shock initiation using Arrhenius kinetics.

Mader<sup>(19)</sup> used Arrhenius kinetics to study the formation of hot spots by the interaction of shock waves with density discontinuities.

However these models, although able to demonstrate the creation of hot spots, were unable to model the initiation of practical explosives.

To this end several attempts have been made. In the following the most important of those attempts will be discussed.

## 2.1 The $P^2t$ CRITERION

In 1969 Walker and Wasley<sup>(28)</sup> proposed a critical energy criterion for the initiation of detonation due to impact. According to that criterion a certain critical energy per unit impact area is necessary for the shock initiation of detonation of a heterogeneous explosive charge. The following equation was derived.

$$PU_p t = P^2 t / \rho_o U_s = E_c \quad (1)$$

where  $P$  is the pressure  
 $U_p$  is the particle velocity  
 $U_s$  is the shock velocity  
 $t$  is the duration of the shock pressure  
 $\rho_o$  is the ambient charge density  
 and  $E_c$  is an experimental constant for a particular explosive charge.

A simpler initiation criterion can be expressed by the equation:

$$P_2 t = C \quad (2)$$

The critical energy equation (1) was derived from the kinetic energy expression

$$E_c = mv^2/2 \quad (3)$$

where  $E_c$  is the critical plate kinetic energy for initiation of an explosive by a flyer plate  
 $m$  is the mass of the flyer plate and  
 $v$  is the velocity of the plate.

However

$$m = A \rho w \quad (4)$$

where  $A$  is the surface area of the plate  
 $\rho$  is the density and  
 $w$  is the thickness of the plate

The duration of the pulse is

$$t = 2 w/U_s \quad (5)$$

where  $U_s$  is the shock velocity in the plate

Moreover from the momentum conservation equation:

$$P - P_o = \rho U_s U_p \quad (6)$$

and since the free surface velocity of the plate is twice the particle velocity,

$$V = 2 U_p \quad (7)$$



Equation (3), because of equations (4), (5), (6) and (7) yields:

$$E_c = AtP^2/\rho U_s \quad (8)$$

$$\text{or} \quad E_c = tP^2/\rho U_s \quad (9)$$

for a unit area of plate. Since for each specific explosive the impedance does not vary significantly with pressure equation (9) can be expressed as:

$$E_c = \alpha P^2 t \quad (10)$$

where  $\alpha$  is a constant.

According to Walker<sup>(25)</sup> the criterion applies most ideally to pure chemical explosives. The critical energy is different for each explosive. Therefore the critical initiation energy will be affected by the following:

- additives to the explosive
- physical and mechanical properties of the explosive
- other energy inputs e.g. heat.

The  $P^2t$  criterion has been useful in describing flyer plate initiation of explosives. It specifies for each initial shock pressure produced by a flying plate a critical time for the onset of detonation. In other words the initiating shock is not appreciably influenced by the energy liberated in the vicinity of the explosive flyer plate interface after the time  $t$ .

Therefore the  $P^2t$  criterion gives a qualitative explanation of explosive behaviour under high velocity impact. However, it does not take into account the mechanism of initiation. Moreover, it has been found that the  $P^2t$  criterion cannot predict the ignition of explosive charges in all cases<sup>(25)</sup>.

## 2.2 THE IGNITION AND GROWTH MODEL

Lee and Tarver<sup>(17)</sup> in 1981 introduced the ignition and growth model. This model, according to them, applies to a wide range of explosives material and a wide range of shock initiation stimuli. In this model the Jones-Wilkins-Lee<sup>(17)</sup> equation of state is used. This equation of state has the form:

$$P = A \left(1 - \frac{w}{R_1 V}\right) \exp(-R_1 V) + B \left(1 - \frac{w}{R_2 V}\right) \exp(-R_2 V) + \frac{wE}{V} \quad (11)$$

where  $P$  is the pressure  
 $V$  is the volume of the material at pressure  $P$  divided by the initial volume of the unreacted explosive  
 $E$  is the internal energy and  
 $A, B, R_1, R_2$  and  $w$  are adjustable constants.

This equation is used for both the unreacted explosive and the reaction products. In the ignition and growth model a small fraction of the explosive is assumed to be ignited by the passage of the shock front and the reaction rate is controlled by the pressure and the surface area as in a deflagration process. The explosive material can be consumed very rapidly since the number of hot spots can be very large. According to the physical model the burning starts at small spherical regions and proceeds

outwards. The following equation is incorporated in the model:

$$\frac{\partial F}{\partial t} = I (1-F)^{x_n r} + G (1-F)^{x_F y} P^z \quad (12)$$

$$\text{with } n = \frac{V_o}{V_1 - 1}$$

where  $F$  is the fraction of the explosive that has reacted  
 $t$  is the time  
 $V_o$  is the initial specific volume of the explosive  
 $V_1$  is the specific volume of the shocked unreacted explosive  
 $P$  is the pressure and  
 $I, x, r, G, y$  and  $z$  are constants.

The first term of equation 12 describes the ignition. The  $n^r$  term is used to investigate various hot spot formation concepts, because  $n$ , the relative compression of the unreacted explosive, can be related to any thermodynamic parameter that may be involved in the initiation process.

Various values of the  $r$  parameter have been proposed; however not one value can apply over an extended range of stimuli or material properties.

The second term in equation 12 describes the growth of the reaction. It is zero when  $F = 0$  or  $F = 1$ , which means, as expected, that there is no growth when the explosive is completely reacted or unreacted. The constant  $G$  corresponds to a surface area to volume ratio and the  $P^z$  term represents a pressure dependent laminar burn rate. Experimentally it has been found that the pressure exponents for laminar deflagration rates

in explosives are generally of the order 0.8 - 1.0 for pressures below 0.1 GPa. According to Tarver and Lee there is some evidence that at higher pressures an abrupt increase in the pressure exponent to approximately 2.0 can occur. The  $(1-F)^x F^y$  term in the growth reaction rate determines the geometry of the hot spots and the value of the  $F$  at which the rate maximizes. Since spherical hot spots are implied  $y$  is set equal to  $2/3$  since  $F^{2/3}$  corresponds to the surface area of spherical hot spots burning outward. The parameter  $x$  is set to  $2/3$  to maximize  $(1-F)^x F^y$  at  $F = 3/4$  which corresponds to the maximum relative volume which hot spots can occupy.

This model has been used successfully to model PBX 9404, PETN, cast TNT and TATB. This means that the model modelled explosives which cover a wide range of sensitivities. However it is difficult to incorporate a model like this since the parameters for equations 11 and 12 for most of explosives are unknown. It is not clear how to obtain them and the model is based on significant assumptions. Therefore it is reasonable to conclude that this model cannot be used for predictive purposes at the present time.

### 2.3 CANMET MODEL

Feng and Hanasaki<sup>(11)</sup> developed a hydrodynamic model based on differential equations derived from the laws of conservation of mass and momentum, together with an equation of state proposed by Tait. Later, Feng et al<sup>(12)</sup> improved the model by using a different equation of state to describe the temperature of air bubbles contained in slurry explosives under dynamic loading. The University of Ottawa researchers<sup>(18)</sup> proposed the use of the Forest Fire Model<sup>(13)</sup> to describe the decomposition rate of the explosive as a function of pressure.

## 2.4 THE FOREST FIRE MODEL

Charles Forest<sup>(13)</sup> in 1976 developed the Forest Fire model. The Forest Fire model is a semiempirical model to describe the explosive decomposition rate as a function of pressure. The model is based on the experimental relationship between the distance of run to detonation in an impacted explosive charge and the initial shock pressure (Pop plot), the reactive and unreactive Hugoniot and the single curve build up hypothesis.

The single curve buildup hypothesis is an approximation relating pressure and distance of run as shown in Figure 4. It states that the buildup process will follow this curve, from left to right regardless of where on the curve the process starts. The hypothesis has been checked experimentally and it has been found valid.

The Pop plot connects the buildup distance with the initial pressure in the shock wave entering the explosive. The Pop plot takes the form

$$x^* = a P_i^b$$

where  $x^*$  is the buildup distance  
 $P_i$  is the initial pressure and  
 $a$  and  $b$  are coefficients of the fit.

The non reactive shock wave in the explosive defines the Hugoniot of the unreacted explosive. The Hugoniot normally takes the form

$$U_s = C_o + S U_p$$

where  $U_s$  is the shock velocity  
 $C_o$  is the bulk sound speed

S is a coefficient  
 $U_p$  is the particle velocity

The same relationship for a reactive shock wave is called the reactive Hugoniot of the explosive.

The Forest Fire technique has been used extensively to model the behaviour of military high explosives. The results in this area have been encouraging. Hence the Forest Fire technique was selected to aid in the modelling of the impact sensitivity of commercial products.



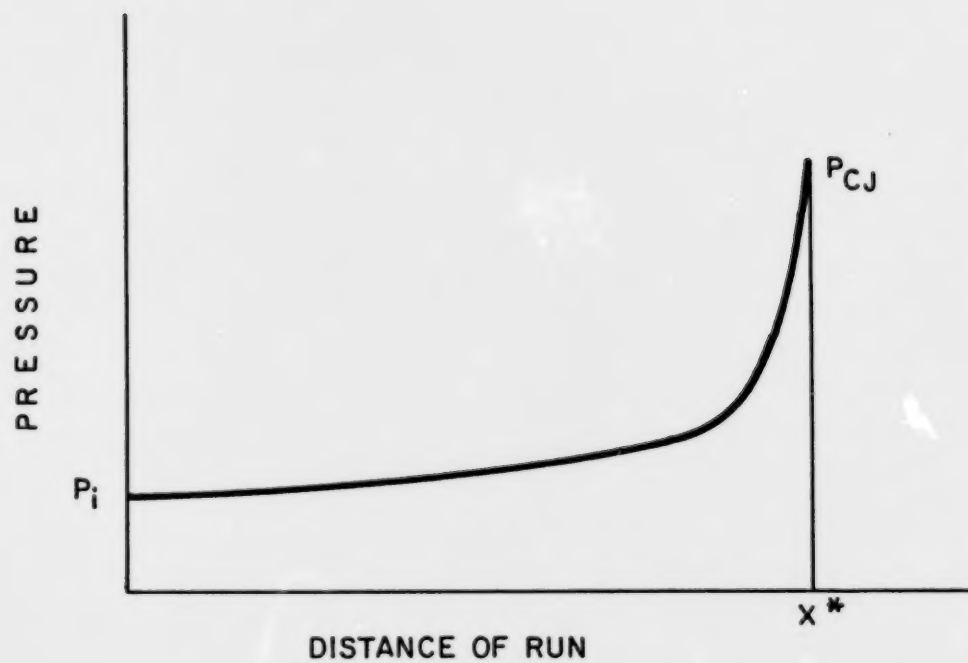


FIGURE 4 : BUILD-UP CURVE FOR HETEROGENEOUS EXPLOSIVES

### CHAPTER THREE

#### DESCRIPTION OF THE FOREST FIRE MODEL

##### 3.0 INTRODUCTION

The Forest Fire model was developed as a result of the need to model the shock initiation of heterogeneous explosives irregardless of the actual nature of the hot spot and its geometrical configuration. The model interprets the Pop plot as a direct description of the shock front. In this chapter the shock measurements on which the model is based will be presented and its mathematical derivation will be outlined.

##### 3.1 SHOCK MEASUREMENTS

Shock waves in heterogeneous military high explosives have been studied using the wedge technique. With this technique a plane uniform shock wave is sent into a wedge shaped piece of explosive and the position of the intersection of the shock wave and the inclined face of the explosive is recorded as a function of time with a streak camera. A typical experimental set up is shown in Figure 5. With this technique a complete time history of the shock wave in the explosive is obtained.

The analysis of the data is normally performed by assuming that the flow is one-dimensional and laminar and that the pressure at the interface where the shock enters the explosive is changing only slowly with time. These assumptions are not exactly correct but no alternative is available. Moreover the magnitude of the errors which can be introduced cannot be estimated.

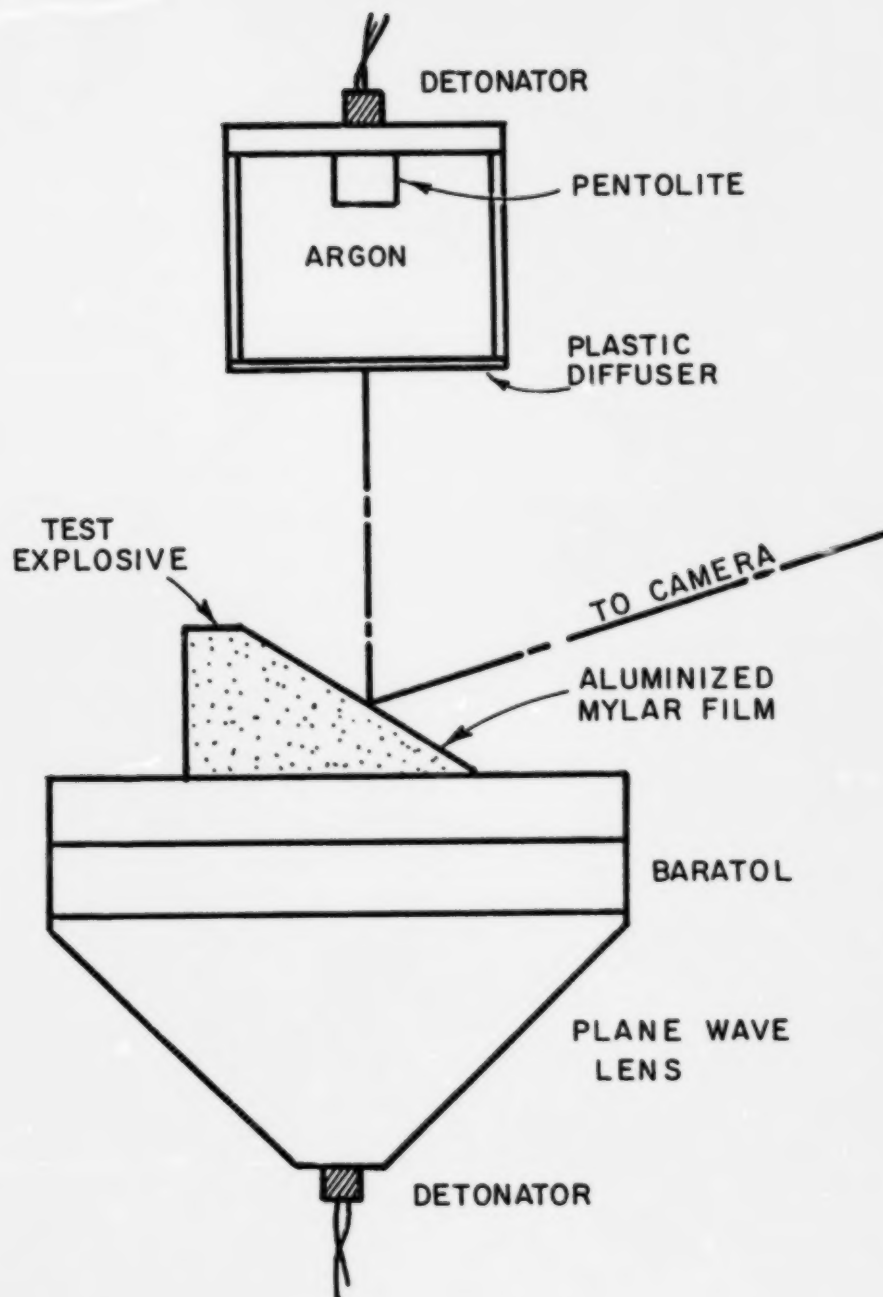


FIGURE 5: WEDGE TYPE ARRANGEMENT

In wedge type experiments the shock wave enters the explosive from a plane wave generator system, which has an inert plate in contact with the explosive. The assumption is made that the pressure and particle velocity are the same on both sides of the attenuator explosive interface, the usual boundary conditions when dealing with shock waves in non reactive medium and a steady state. However initiation is not a steady state and these boundary conditions cannot be exactly correct. The particle velocity of the attenuator can be found by determining the Hugoniot of the attenuator and the relationship between shock velocity and attenuator thickness for the given experimental system. Thus the pressure in the attenuator can be calculated by the relationship

$$P_a = \rho_a U_{sa} U_{pa} \quad (3.1)$$

where  $P_a$  is the pressure in the attenuator  
 $\rho_a$  is the initial density of the attenuator  
 $U_{sa}$  is the shock velocity in the attenuator  
 $U_{pa}$  is the particle velocity in the attenuator

Other experimental data include the initial explosive density  $\rho_o$  and the initial shock velocity in the explosive. The latter is measured from the streak camera record.

Since the shock pressure and the particle velocity in the attenuator are known the pressure  $P_e$  and the particle velocity  $U_{pe}$  in the explosive are found by determining the intersection of the rarefaction locus of the attenuator approximated by reflecting the attenuator Hugoniot along the line  $U_{pa} = \text{constant}$  and the locus for the state of the explosive, given by the conservation of momentum relation

$$P_e = \rho_e U_{pe} U_{se} \quad (3.2)$$

where  $P_e$  is the pressure in the explosive  
 $\rho_e$  is the initial density of the explosive  
 $U_{pe}$  is the particle velocity in the explosive  
 $U_{se}$  is the shock velocity in the explosive

The process is illustrated in Figure 6. It should be noted that when the shocked material is an explosive the above equation (3.2) holds for a steady state detonation. However the process of initiation cannot be regarded as steady state. The explosive reacts to some small extent immediately after the shock front and the extent of reaction increases as the shock wave proceeds. In the region near the explosive attenuator interface where a very small part of the explosive reacts the above equation can be assumed to hold with sufficient accuracy.

Popolato and Ramsay<sup>(22)</sup> found that the distance of run to high order detonation and the initial pressure in the explosive are related linearly when they are expressed by their logarithms. The plot  $\log P$  versus  $\log x^*$  where  $P$  is pressure and  $x$  is the distance of run is called Pop plot after its originator A. Popolato. Typical Pop plots for military explosives are shown in Figure 7.

### 3.2 MATHEMATICAL DERIVATION OF THE FOREST FIRE MODEL

The Forest Fire model is based on the previously mentioned experimental data and detonation theory. In the following it will be derived analytically.

The relation for the model are the following:

- (1) The Pop plot. The Pop plot is given by the expression

$$\ln (\text{run}) = a_1 + a_2 \ln (P - a_3) \quad (3.3)$$

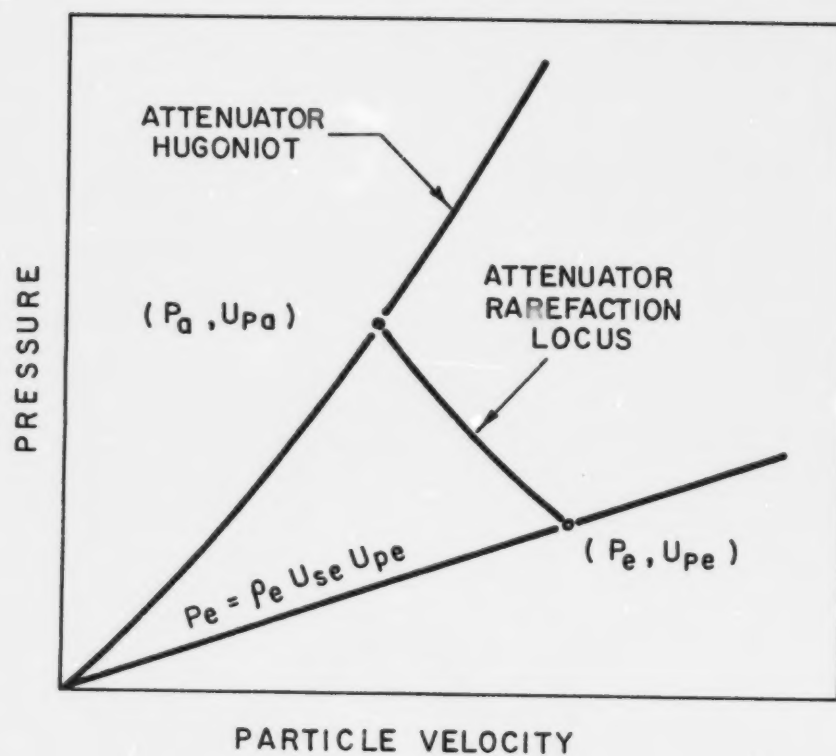


FIGURE 6: GRAPHICAL METHOD OF OBTAINING SHOCK PRESSURE AND PARTICLE VELOCITY IN UNDER-INITIATED EXPLOSIVE.



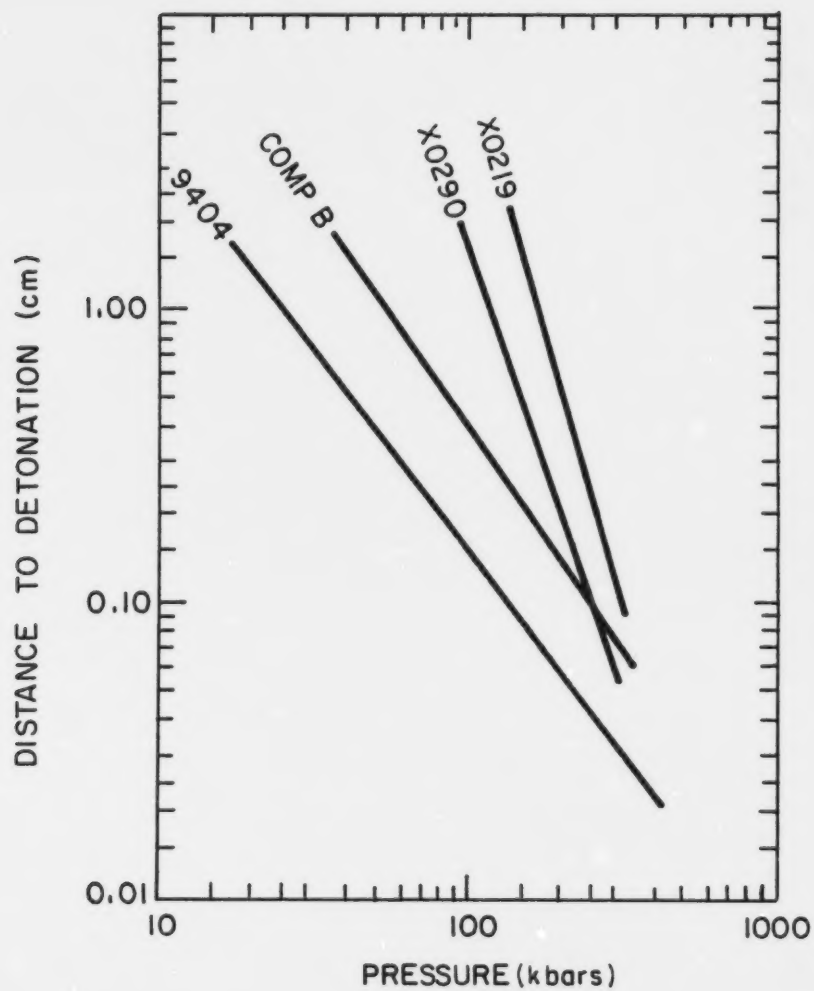


FIGURE 7 : TYPICAL POP PLOTS FOR MILITARY HIGH EXPLOSIVES

where  $P$  is the input shock pressure in the explosive  
 $run$  is the run distance to high order detonation  
 and

$a_1, a_2, a_3$  are constants depending on the explosive

- (2) The reactive Hugoniot is assumed to be described by a shock velocity particle velocity fit.

$$U_s = C + S U_p \quad (3.4)$$

The reactive Hugoniot gives from the shock jump conditions for  $P_0 = 0$ .

$$P = \rho_0 U_s U_p \quad (3.5)$$

$$V = V_0 (U_s - U_p) / U_s \quad (3.6)$$

$$I = U_p^2 / 2 \quad (3.7)$$

where  $P$  is the pressure  
 $\rho_0$  is the initial density of the explosive  
 $V$  is the specific volume of the explosive  
 $V_0$  is the initial specific volume of the explosive  
 $I$  is the specific internal energy  
 $U_s$  is the shock velocity  
 $U_p$  is the particle velocity

- (3) The HOM equation of state. The HOM equation of state which is described in the following chapter can be expressed as:

$$P = H(V, I, W) \quad (3.8)$$

where  $V$  is the specific volume  
 $I$  is the internal energy  
 $W$  is the mass fraction of the undecomposed explosive.

The Lagrangian coordinates  $m, \tau$  are related to the Eulerian coordinates  $x, t$  by the following equations:

$$\frac{\partial}{\partial m} = \frac{1}{\rho} \frac{\partial}{\partial x} \quad (3.9)$$

and 
$$\frac{\partial}{\partial \tau} = \frac{\partial}{\partial t} + U \frac{\partial}{\partial x} \quad (3.10)$$

Equation (3.8) yields

$$\frac{\partial P}{\partial \tau} = \frac{\partial H}{\partial V} \frac{\partial V}{\partial \tau} + \frac{\partial H}{\partial I} \frac{\partial I}{\partial \tau} + \frac{\partial H}{\partial W} \frac{\partial W}{\partial \tau} \quad (3.11)$$

or

$$\frac{\partial W}{\partial \tau} = \frac{\frac{\partial H}{\partial V} \frac{\partial V}{\partial \tau} + \frac{\partial H}{\partial I} \frac{\partial I}{\partial \tau} - \frac{\partial P}{\partial \tau}}{-\frac{\partial H}{\partial W}} \quad (3.12)$$

Therefore for the reaction rate calculation the derivatives of the right hand side of equation (3.12) must be calculated.

From equations (3.4) and (3.5) it follows that:

$$U_p = \frac{-\rho_o C + \sqrt{(\rho_o C)^2 + 4P\rho_o S}}{2\rho_o S} \quad (3.13)$$

From (3.4) and (3.13)

$$U_s = \frac{-\rho_o C + \sqrt{(\rho_o C)^2 + 4P\rho_o S}}{2\rho_o} \quad (3.14)$$

From equations (3.6) and (3.7) since  $U_s$ ,  $U_p$  are known  $V$  and  $I$  can be calculated. Then knowing  $P, V$ ,  $I$  the HOM equation can be solved to provide  $W$ . Then the derivatives

$$\frac{\partial H}{\partial V}, \quad \frac{\partial H}{\partial I} \quad \text{and} \quad \frac{\partial H}{\partial W}$$

can be calculated at that state point. The derivatives

$$\frac{\partial V}{\partial \tau}, \quad \frac{\partial I}{\partial \tau} \quad \text{and} \quad \frac{\partial P}{\partial \tau}$$

will be calculated in the following. Initially the fluid flow equations in Lagrangian coordinates will be determined:

From the equation of continuity

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x} (\rho U) = 0$$

or

$$\frac{\partial \rho}{\partial t} + U \frac{\partial \rho}{\partial x} + \rho \frac{\partial U}{\partial x} = 0$$

or

$$\frac{\partial \rho}{\partial \tau} + U \frac{\partial \rho}{\partial x} = - \rho \frac{\partial U}{\partial x}$$

or

$$- \frac{1}{\rho^2} \left( \frac{\partial \rho}{\partial t} + U \frac{\partial \rho}{\partial x} \right) = \frac{1}{\rho} \frac{\partial U}{\partial x}$$

$$\text{or} \quad \frac{\partial}{\partial t} \left( \frac{1}{\rho} \right) + U \frac{\partial}{\partial x} \left( \frac{1}{\rho} \right) = \frac{1}{\rho} \frac{\partial U}{\partial x}$$

$$\text{or} \quad \frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} = \frac{1}{\rho} \frac{\partial U}{\partial x} \quad (3.15)$$

From (3.9), (3.10) and (3.15)

$$V_{\tau} = U_m \quad (3.16)$$

$$\text{where} \quad V_{\tau} = \frac{\partial V}{\partial \tau}$$

$$\text{and} \quad U_m = \frac{\partial U}{\partial m}$$

From the equation of motion

$$\rho \frac{\partial U}{\partial t} + \rho U \frac{\partial U}{\partial x} = - \frac{\partial P}{\partial x}$$

$$\text{or} \quad \frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} = - \frac{1}{\rho} \frac{\partial P}{\partial x} \quad (3.17)$$

From (3.9), (3.10) and (3.17)

$$U_{\tau} = -P_m \quad (3.18)$$

$$\text{where} \quad U_{\tau} = \frac{\partial U}{\partial \tau}$$

and

$$P_m = \frac{\partial P}{\partial m}$$

The equation of conservation of energy in the case of a plane one dimensional wave yields:

$$\rho \frac{d}{dt} \left( I + \frac{1}{2} (U^2) \right) = - \frac{\partial}{\partial x} (PU)$$

or 
$$\frac{\partial I}{\partial t} + U \frac{\partial U}{\partial t} = - \frac{1}{\rho} \frac{\partial}{\partial x} (PU)$$

or 
$$\frac{\partial I}{\partial t} + U \frac{\partial U}{\partial t} = - \frac{1}{\rho} \frac{\partial P}{\partial x} U - \frac{1}{\rho} \frac{\partial U}{\partial x} P$$

or because of (3.9)

$$\frac{\partial I}{\partial t} + U \frac{\partial U}{\partial t} = - P_m U - U_m P$$

or 
$$\frac{\partial I}{\partial t} + U \frac{\partial U}{\partial t} + P_m U = - U_m P$$

or 
$$\frac{\partial I}{\partial t} + U \left( \frac{\partial U}{\partial t} + P_m \right) = - U_m P$$

or because of (3.10)

$$\frac{\partial I}{\partial t} + U \left( U_\tau - U \frac{\partial U}{\partial x} + P_m \right) = - U_m P$$

or because of (3.18)

$$\frac{\partial I}{\partial t} + U \left( - \frac{\partial U}{\partial x} U \right) = - U_m P$$

or

$$\frac{\partial I}{\partial t} + U \left( - \frac{\partial E_{kin}}{\partial x} \right) = - U_m P \quad (3.19)$$

where  $E_{kin}$  is the kinetic energy.



Moreover  $E_{kin} = I - E_o$ .

where  $I$  is the total energy  
and

$E_o$  is the initial energy

(3.19) and (3.20) by substitution yield:

$$\frac{\partial I}{\partial t} + U \left( -\frac{\partial E_o}{\partial x} + \frac{\partial I}{\partial x} \right) = -U_m P$$

or

$$\frac{\partial I}{\partial t} + U \frac{\partial I}{\partial x} = -U_m P$$

since

$$\frac{\partial E_o}{\partial x} = 0$$

$$\text{or } I_\tau = -U_m P$$

(3.21)

$$\text{where } I_\tau = \frac{\partial I}{\partial \tau}$$

$$\text{or because of (3.16) } I_\tau = V_\tau P$$

(3.22)

Moreover from equation 3.10 it is

$$\frac{dP}{dt} = \frac{dP}{d\tau} - U \frac{\partial P}{\partial x} \quad (3.23)$$

Assuming a square wave  $\frac{\partial P}{\partial x} = 0$

$$\text{Therefore } \frac{dP}{dt} = \frac{dP}{d\tau} \quad (3.24)$$

Moreover

$$\frac{dP}{dt} = \frac{dP}{drun} \frac{drun}{dt} =$$

$$\frac{dP}{drun} U_s \quad (3.25)$$

From equation (3.3) after differentiation

$$\frac{dP}{drun} = \frac{P - a_3}{a_2 run P} \quad (3.26)$$

From (3.25), (3.26)

$$\frac{dP}{d\tau} = \frac{P - a_3}{a_2 run P} U_s \quad (3.27)$$

Furthermore

$$\frac{dU}{dt} = \rho_o U_s U_m + U_\tau \quad (3.28)$$

$$\text{Moreover } \frac{dU}{dt} = \frac{dU}{dP} \frac{dP}{dt} \quad (3.29)$$

$$\text{However } P = \rho_o U_s U$$

$$\text{or } \frac{P}{\rho_o (C+SU)} = U$$

$$\text{or } PV_o = UC + SU^2$$

and by differentiation

$$V_o = \frac{dU}{dP} C + 2 U \frac{dU}{dP} S$$

$$\text{or } \frac{V_o}{C + 2 SU} = \frac{dU}{dP} \quad (3.30)$$

(3.29) and (3.30) yield

$$\frac{dU}{dt} = \frac{V_o}{C + 2 SU} \frac{dP}{dt} \quad (3.31)$$

From equation (3.28)

$$U_m = (dU/dt - U_\tau) / \rho_o U_s \quad (3.32)$$

Because of (3.16) and (3.18)

$$V_\tau = \frac{dU/dt + P_m}{\rho_o U_s}$$

Assuming that  $P_m = 0$

$$V_\tau = \frac{dU/dt}{\rho_o U_s} \quad (3.33)$$

(3.33) because of (3.30) gives

$$V_\tau = \frac{V_o}{C + 2 SU} \frac{1}{\rho_o U_s} \frac{dP}{dt} \quad (3.34)$$

or

$$V_\tau = \frac{V_o}{C + 2 SU} \frac{1}{\rho_o U_s} \frac{P - a_3}{a_2 - \text{run } P} U_s \quad (3.35)$$

Moreover from (3.21) and (3.35) we have

$$I_\tau = -P \frac{V_o}{C + 2 SU} \frac{1}{\rho_o U_s} \frac{P - a_3}{a_2 - \text{run } P} U_s \quad (3.36)$$

Therefore  $W_T$  from equation (3.12) can be calculated.

The function  $(-1/W_T)$  is then fit to a polynomial of the form

$$\ln \left( -\frac{W_T}{W} \right) = \sum_{i=0}^n A_i P_i \quad (3.36)$$

In other words the rate is expressed as a function of pressure through the following relationship:

$$\ln (\text{rate}) = A_0 + A_1 P + A_2 P^2 + \dots A_n P^n \quad (3.37)$$

### 3.3 THE HOM EQUATION OF STATE

In the Forest Fire technique and in the hydrodynamic calculations the HOM equation of state for solids and gases is used extensively.

The HOM equation of state calculates the pressures and temperatures, given the internal energy, specific volume and mass fraction of unreacted material for solids, gases and mixtures.

#### 3.3.1 HOM for Gases

The pressure, volume temperature and internal energy values are calculated on the adiabat passing through the C-J point by means of a thermohydrodynamic code (e.g. Tiger) and least square fits are made according to the following equations:

$$\ln P_i = A + B \ln V_g + C (\ln V_g)^2 + D (\ln V_g)^3 + E (\ln V_g)^4 \quad (3.38)$$

$$\ln I'_i = k + L \ln P + M (\ln P)^2 + N (\ln P)^3 + O (\ln P)^4 \quad (3.39)$$

$$\ln T_i = Q + R (\ln V_g) + S (\ln V_g)^2 + T (\ln V_g)^3 + U (\ln V_g)^4 \quad (3.40)$$

$$I = I' - Z \quad (3.41)$$

where  $P_i$  is the pressure  
 $I_i$  is the energy  
 $T_i$  is the temperature  
 $V_g$  is the specific volume  
 and  $Z$  is such that  $I'$  is positive through the fit

The Gruneisen equation of state gives the pressure at other thermodynamic points away from the isentrope. The Gruneisen equation of state is

$$P = P_i + \frac{\gamma}{V} (I - I_i) \quad (3.42)$$

where  $\gamma = V \left( \frac{\partial P}{\partial I} \right)_V$  (3.43)

However

$$\left( \frac{\partial P}{\partial I} \right)_V = \left( \frac{\partial P}{\partial S} \right)_V \left( \frac{\partial S}{\partial I} \right)_V = - \frac{1}{T} \left( \frac{\partial T}{\partial V} \right)_S \quad (3.44)$$

Moreover

$$- \frac{1}{T} = \left( \frac{\partial \ln T}{\partial \ln V} \right)_S = \frac{V}{T} \left( \frac{\partial T}{\partial V} \right)_S \quad (3.45)$$

From (3.43), (3.44) and (3.45)

$$\gamma = \frac{1}{\beta} \quad (3.46)$$

$\gamma$  can be evaluated on the adiabat as a function of  $V$  as follows:

From equation (3.40) by differentiation

$$\left( \frac{\partial \ln T}{\partial \ln V} \right)_S = R + 2 S \ln V + 3T \ln V_g + 4U (\ln V_g) \quad (3.47)$$

From (3.47) and (3.45) it follows

$$-\frac{1}{\beta} = R + 2 S \ln V + 3T (\ln V_g) + 4U (\ln V_g) \quad (3.48)$$

(3.42) because of (3.46) yields

$$P = P_i + \frac{I - I_i}{\beta V_g} \quad (3.49)$$

Moreover assuming that  $C_v$  is constant

$$T = T_i + \frac{I - I_i}{C_v} \quad (3.50)$$

### 3.3.2 HOM for Solids

For most condensed materials the relationship between shock velocity and particle velocity is linear. Therefore

$$V_s = C + S U_p \quad (3.51)$$

where  $U_s$  is the shock velocity  
 $U_p$  is the particle velocity  
 $C$  and  $S$  are constants

Equation (3.51) together with the shock jump equations give enough information to determine the Hugoniot pressure and the Hugoniot specific internal energy as a function of energy, initial density, initial pressure and initial energy.

The shock jump equations are:

$$\rho_o U_s = \rho (U_s - U_p) \quad (3.52) \text{ Conservation of mass}$$

$$P_H - P_o = \rho_o U_s U_p \quad (3.53) \text{ Conservation of momentum}$$

$$E - E_o = \frac{1}{2} (P_H + P_o) \left( \frac{1}{\rho_o} - \frac{1}{\rho} \right) \quad (3.54) \text{ Conservation of Energy}$$

where  $\rho_o$  is the initial density  
 $\rho$  is the density of the condensed component  
 $P_H$  is the Hugoniot pressure  
 $P_o$  is the initial pressure  
 $E$  is the energy  
 $E_o$  is the initial energy

Equation (3.53) because of (3.51) yields:

$$P_H = \rho_o \frac{U_s^2 - C U_s}{S} + P_o \quad (3.55)$$

Equation (3.52) because of (3.51) yields:



$$U_S = \frac{C V_o}{V_o - S (V_o - V)} \quad (3.56)$$

where  $V_o = \frac{1}{\rho_o}$

(3.53) because of (3.56) yields:

$$P_H = \left( \frac{C}{V_o - S (V_o - V)} \right)^2 (V_o - V) + P_o \quad (3.57)$$

(3.57) and (3.54) give pressure and energy along the Hugoniot. However pressure and energy are required off the Hugoniot as well.

A Taylor expansion to first order around the Hugoniot gives:

$$P = P_H + (I - I_H) \left( \frac{\partial P}{\partial I} \right)_V \quad (3.58)$$

The Gruneisen gamma is defined as

$$\gamma = V \left( \frac{\partial P}{\partial T} \right)_V \quad (3.59)$$

From (3.58) and (3.59)

$$P = P_H + \left( \frac{I - I_H}{V} \right) \gamma \quad (3.60)$$

The temperature on the Hugoniot  $T_H$  is calculated by the Walsh - Christian technique. Finally the logarithm of the temperature is fitted to a polynomial in  $\ln(V)$  by a least square fit.

Therefore:

$$\ln T_H = F + G(\ln V) + H(\ln V)^2 + I(\ln V)^3 + J(\ln V)^4 \quad (3.61)$$

Assuming that the heat capacity

$$C_V = \left( \frac{\partial I}{\partial T} \right)_V$$

is constant the temperatures off the Hugoniot can be calculated by the following expression

$$T = T_H + \frac{I - I_H}{C_V} \quad (3.62)$$

### 3.3.3 HOM for Mixtures of Solids and Gases

In the case of a mixture of solids and gases in the case of a reacting explosive, temperature and pressure equilibrium are assumed between the different phases.

Therefore

$$P_g = P_s = P \quad (3.63)$$

$$T_g = T_s = T \quad (3.64)$$

where  $P$  and  $T$  are the Pressure and Temperature and the subscripts  $g, s$  denote gas and solid respectively.

Moreover if  $W$  is the mass fraction of the undecomposed explosive

$$V = W V_s + (1 - W) V_g \quad (3.65)$$

$$I = W I_s + (1 - W) I_g \quad (3.66)$$

where  $V$  is the specific volume

and  $I$  is the specific energy of the mixture.

Equation (3.62) when multiplied by  $W C_v$  yields:

$$T_S W C_v = T_H W C_v + (I_S - I_H) W \quad (3.67)$$

Equation (3.50) when multiplied by  $(1-W) C'_v$  yields:

$$T_g (1 - W) C'_v = T_1 (1 - W) C'_v + (I_g - I_1) (1 - W) \quad (3.68)$$

where the subscripts  $g$  and  $s$  denote gas and solids respectively and  $C_v$  and  $C'_v$  the heat capacities at constant volume for solid and gas respectively.

(3.67) and (3.68) by addition give:

$$T_S W C_v + T_g (1 - W) C'_v = T_H W C_v + (I_S - I_H) W +$$

$$T_1 (1 - W) C'_v + (I_g - I_1) (1 - W) \quad (3.69)$$

or because of (3.66)

$$T = \frac{[I - (W I_H + (1-W) I_1) + W C_v T_H + (1-W) C'_v T_1]}{W C_v + (1-W) C'_v} \quad (3.70)$$

The above equation (3.70) expresses the temperature of the mixture in terms of  $V_s$  and  $V_g$  since  $I_H$ ,  $I_i$ ,  $T_H$ ,  $T_i$  are expressed as functions of  $V_s$  and  $V_g$  through equations (3.38), (3.39), (3.40).

From equations (3.49), (3.60) and (3.63) it is

$$P_H + \left( \frac{I_s - I_H}{V_s} \right) \gamma = P_i + \frac{I_g - I_i}{\beta V_g}$$

or

$$P_H - P_i + \frac{I_s - I_H}{V_s} \gamma - \frac{I_g - I_i}{\beta V_g} = 0 \quad (3.71)$$

However

$$I_s - I_H = C_v (T - T_H) \quad (3.72)$$

$$I_g - I_i = C'_v (T - T_i) \quad (3.73)$$

Therefore (3.71) and (3.72) and (3.73) yield:

$$P_H - P_i + \left( \frac{\gamma_s C_v}{V_s} - \frac{C'_v}{\beta V_g} \right) T - \left( \frac{\gamma_s C_v T_H}{V_s} - \frac{C'_v T_i}{\beta V_g} \right) = 0 \quad (3.74)$$

Since  $V$ ,  $I$  and  $W$  are known, an iterative technique can be used to solve for  $V_s$  or  $V_g$ . Once  $V_s$ ,  $V_g$  are known  $P$  and  $T$  can be calculated from equations (3.70), (3.74).

## CHAPTER FOUR

### THE HYDRODYNAMIC CODE HYDREL

#### 4.0 INTRODUCTION

The hydrodynamic calculations were based on an existing non reactive code, "TROT" written by L. Seaman of Stanford Research Institute. This code was changed significantly so that the main emphasis is on the burning of the explosive and the characteristics of the shock initiation.

For that purpose the Forest Fire model the HOM equation of state, the sharp shock burn and the Arrhenius burn models were incorporated in the program. In the following the computer program will be described.

#### 4.1 THE COMPUTER PROGRAM

The computer program, "HYDREL" is a finite difference Lagrangian code. For the calculations the material is divided into small cells or continuum elements by means of a grid. A typical grid describing the impact of a flyer plate on an explosive target is shown in Figure 7. The computations proceed forward in time in small increments. At each increment calculations are made of stress, velocity, displacement and energies at each cell and coordinate point.

A simplified flow chart of the program is shown in Figure 9.

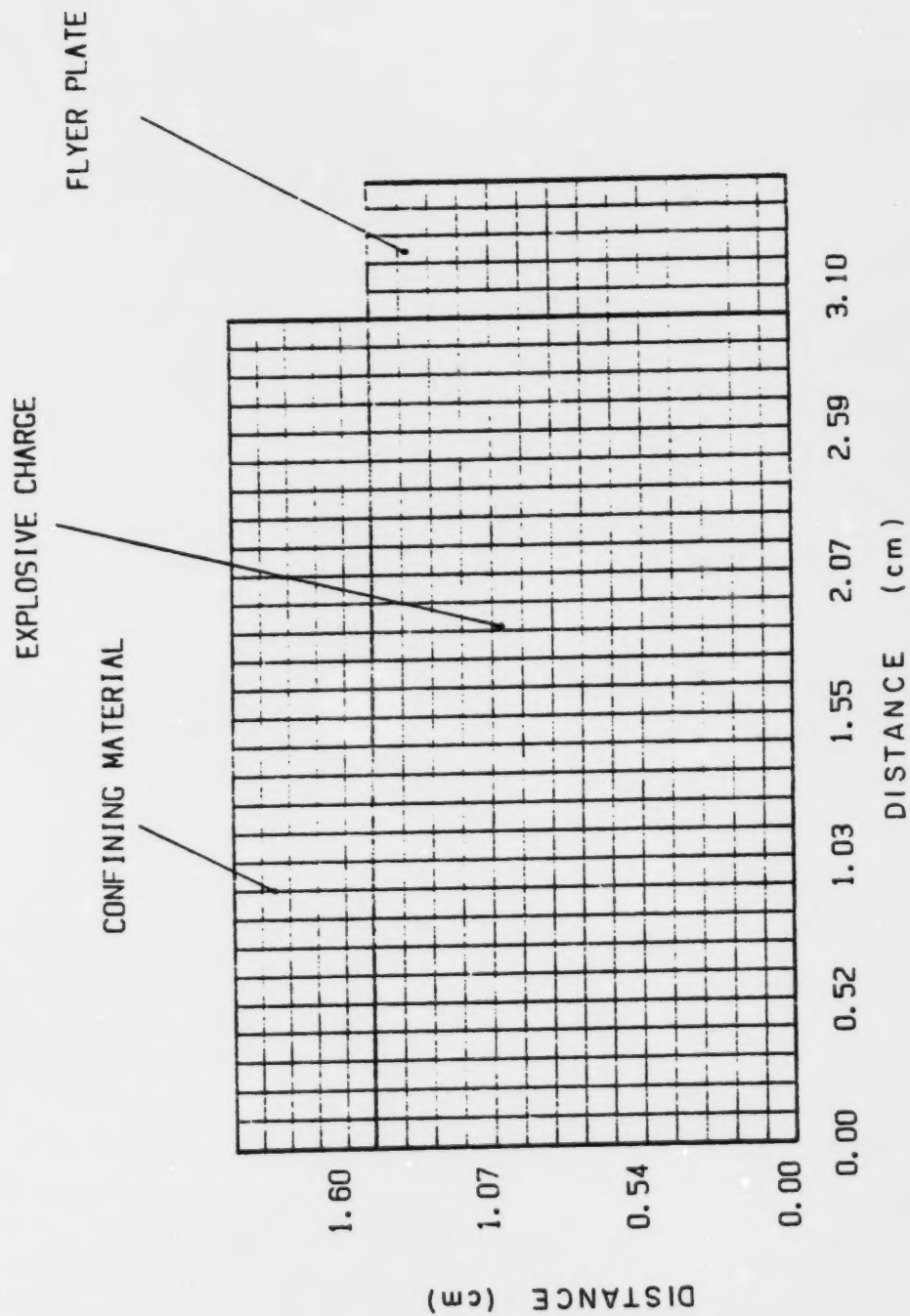


FIGURE 8: TYPICAL GRID FOR THE HYDRODYNAMIC MODEL 'HYDREL'

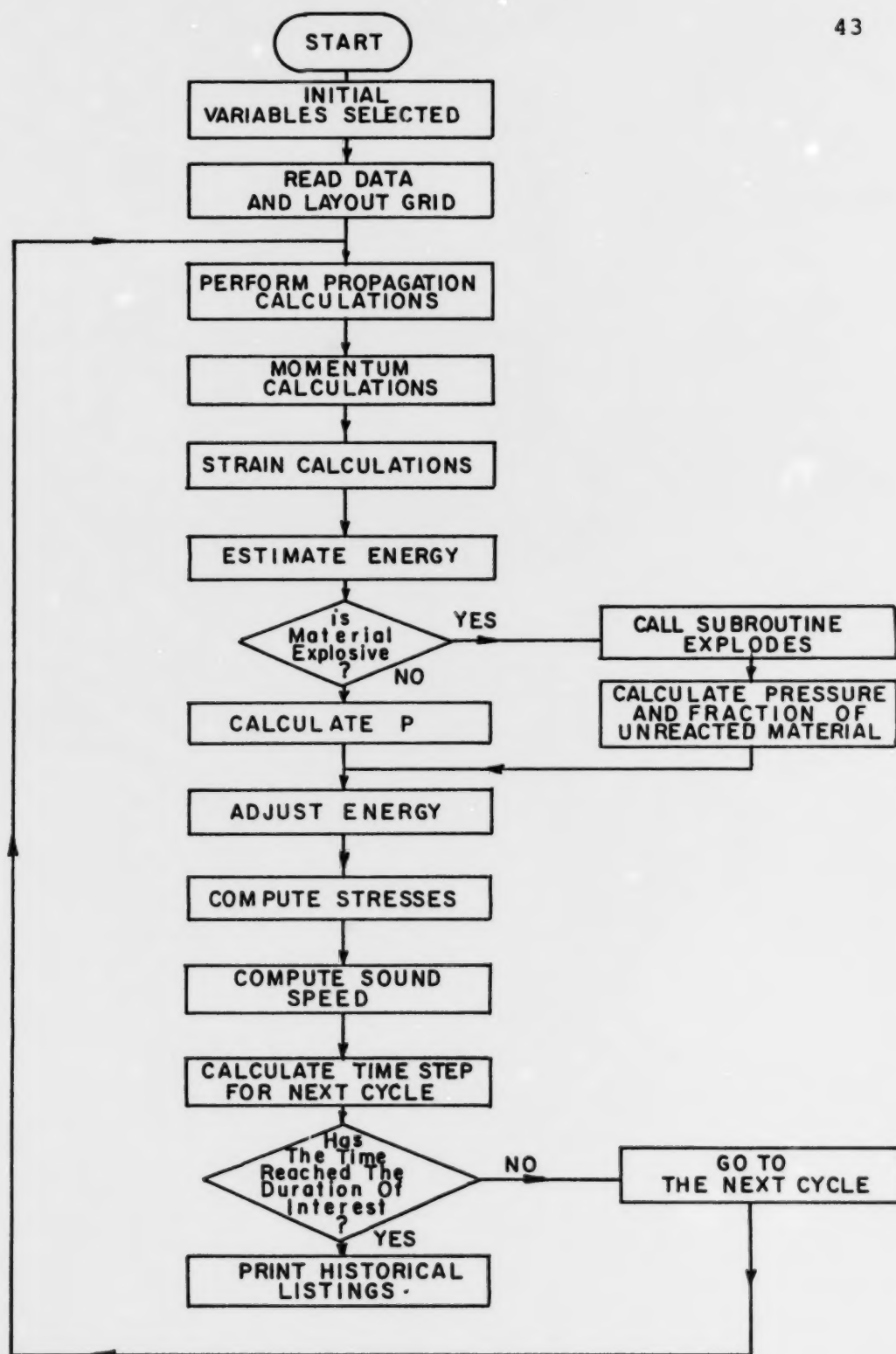


FIGURE 9: SIMPLIFIED FLOW CHART OF THE "HYDREL" COMPUTER CODE



#### 4.1.1 Propagation Calculations

As it was mentioned in the previous section the material is divided into discrete units or cells. Coordinate quantities (velocity and location) are defined only at cell boundaries and at full or half time increments. Figure 9 serves as a guide to the approach taken. It shows the cell quantities on a time-distance plot. For simplicity it contains only one spatial direction (in this case the Eulerian direction  $X$ ). The following is a discussion of the propagation calculations according to L. Seaman.

The momentum calculation is used to determine velocity changes. For example the stresses  $\sigma_{j,n}$   $\sigma_{j+1,n}$  in adjacent cells (mid points) at the time step  $n$  determine the forces on the mass centered at the point  $(J,n)$ . From the momentum calculation:

$$F = m a \quad (4.1)$$

where  $F$  is the force  
 $m$  is the mass of the cell and  
 $a$  is the acceleration of the centre of the cell.

Therefore the acceleration is known. The acceleration of the mass at  $(J,n)$  determines the change in velocity  $\dot{X}_{(n-1)/2}$  to  $\dot{X}_{(n+1)/2}$ . From the new velocity the coordinate position  $X_{n+1}$  at time step  $n+1$  is known.

With the coordinate positions at time  $n+1$  known, the strains and density can also be calculated. The stresses at time step  $n+1$   $\sigma_{j,n+1}$  are obtained from the strains and the density using the constitutive relations.

The procedure is continued to the right through each cell for each time increment. This process is repeated until the time has reached the duration of interest.

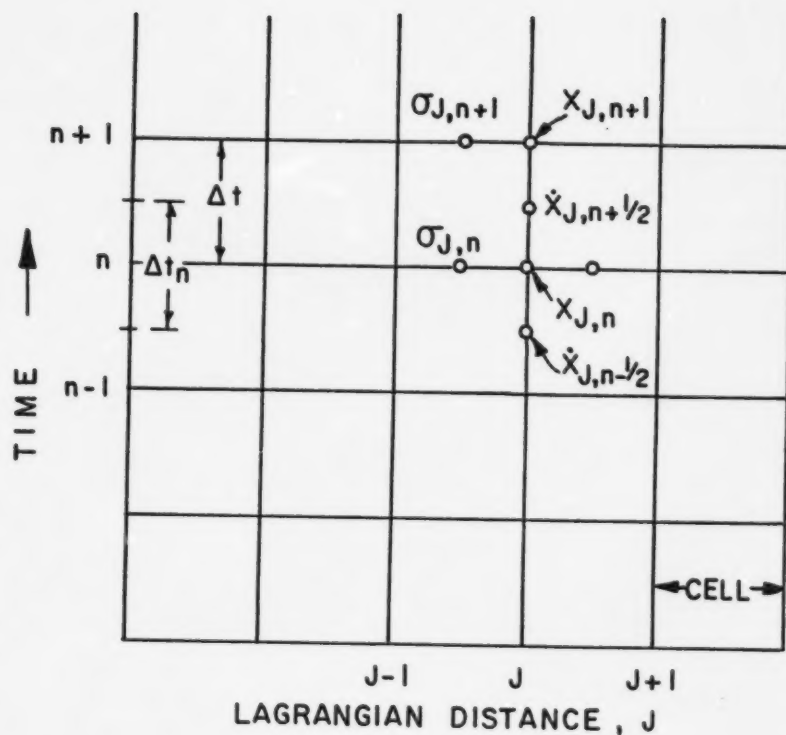


FIGURE 10: FINITE-DIFFERENCE GRID SHOWING LOCATIONS OF VARIABLES USED IN THE MOMENTUM CONSERVATION RELATIONS (Seaman, 1976).

For the shock wave propagation the conservation relations for mass, momentum and energy are of paramount importance. In the following it will be described how these relations are satisfied in the computer code.

Mass is conserved by using Lagrangian cells that maintain a constant mass throughout the event.

Momentum conservation relations are used to obtain the coordinate motions and energy conservation is the basis of the internal energy computation.

In deriving momentum conservation relations, it is possible to use a discretization of the differential equations of momentum conservation or to consider force balances around a finite element.

The finite element approach was adopted for the hydrodynamic model. The following is a discussion of the finite element approach given by Seaman<sup>(23)</sup>.

The steps in the calculations are to isolate a volume element for which the acceleration and velocity are computed, compute the forces acting on that element and compute the mass of the element.

Two types of quadrilateral cell are defined for the wave propagation calculation. Both are shown in Figure 11. Cell A is the natural cell surrounded by four coordinate points. In this cell stresses and strains are homogeneous. The momentum calculation determines the velocities of the coordinate points. For these calculations cell B, containing the mass around a coordinate point is used.

The calculations are broken into four parts corresponding

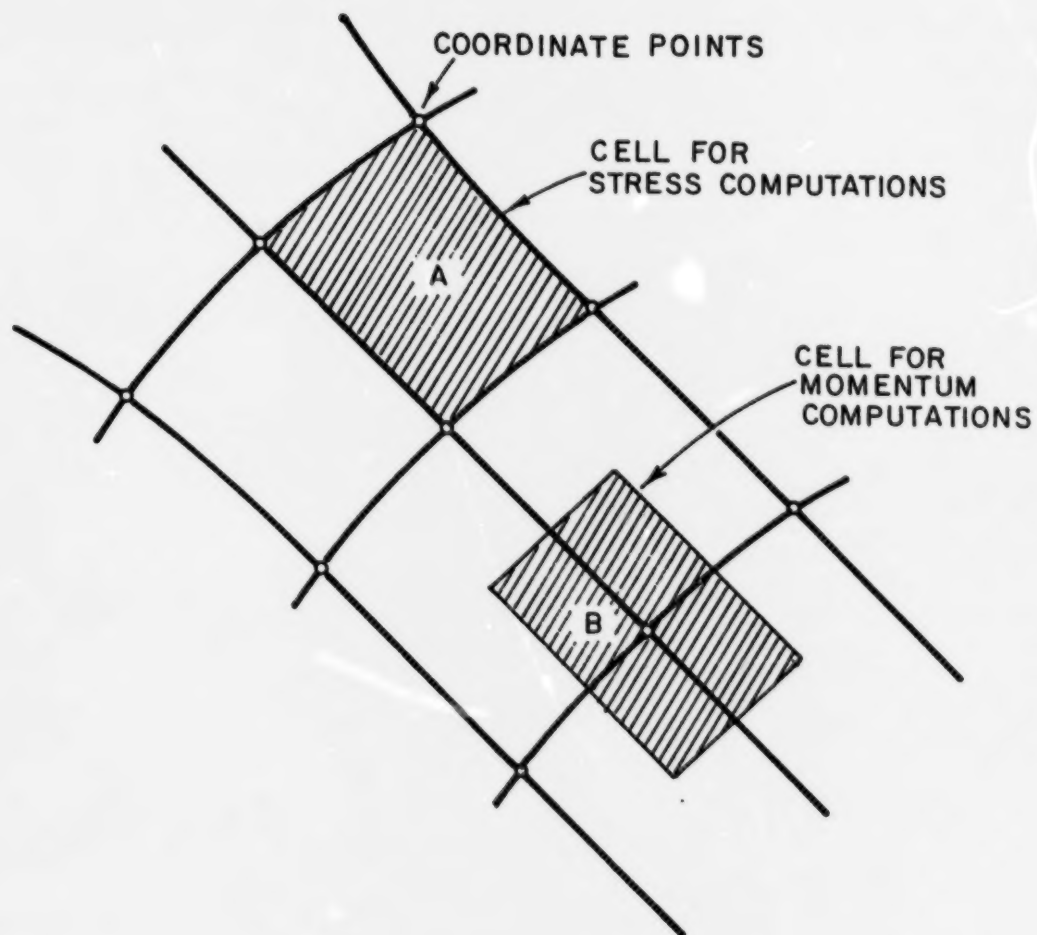


FIGURE 11: TYPES OF QUADRILATERAL CELLS USED IN THE WAVE PROPAGATION CALCULATIONS (after Seaman, 1976)

to each of the surrounding parts. A typical example is shown in Figure 12. Cross sections are shown in Figure 12 to differentiate between the axisymmetric and the planar case both of which are treated in the hydrodynamic code.

At point O the X,Y coordinates are such that

$$X_o = \frac{X_1 + X_2 + X_3 + X_4}{4} \quad Y_o = \frac{Y_1 + Y_2 + Y_3 + Y_4}{4} \quad (4.2)$$

For the planar cell, the areas of the shaded element on which stresses act in the X and Y directions are:

$$A_{xx} = \frac{1}{2} (Y_2 - Y_4) \quad (4.3)$$

$$A_{yy} = \frac{1}{2} (X_4 - X_2) \quad (4.4)$$

For axisymmetric cells

$$A_{xx} = \frac{d\theta}{4} (Y_2 - Y_4) \left( \frac{Y_2 + Y_4}{2} + Y_3 \right) \quad (4.5)$$

$$A_{yy} = \frac{d\theta}{2} \left[ \left( \frac{Y_2 + Y_3}{2} + Y_o \right) \left( X_o - \frac{X_2 + X_3}{2} \right) - \left( \frac{X_3 + X_4}{2} + Y_o \right) \left( X_o - \frac{X_3 + X_4}{2} \right) \right] \quad (4.6)$$

For the axisymmetric case the area in the x-y plane on which the stress acts is broken into two portions  $A_o$  and  $A_3$  as shown in Figure 12.

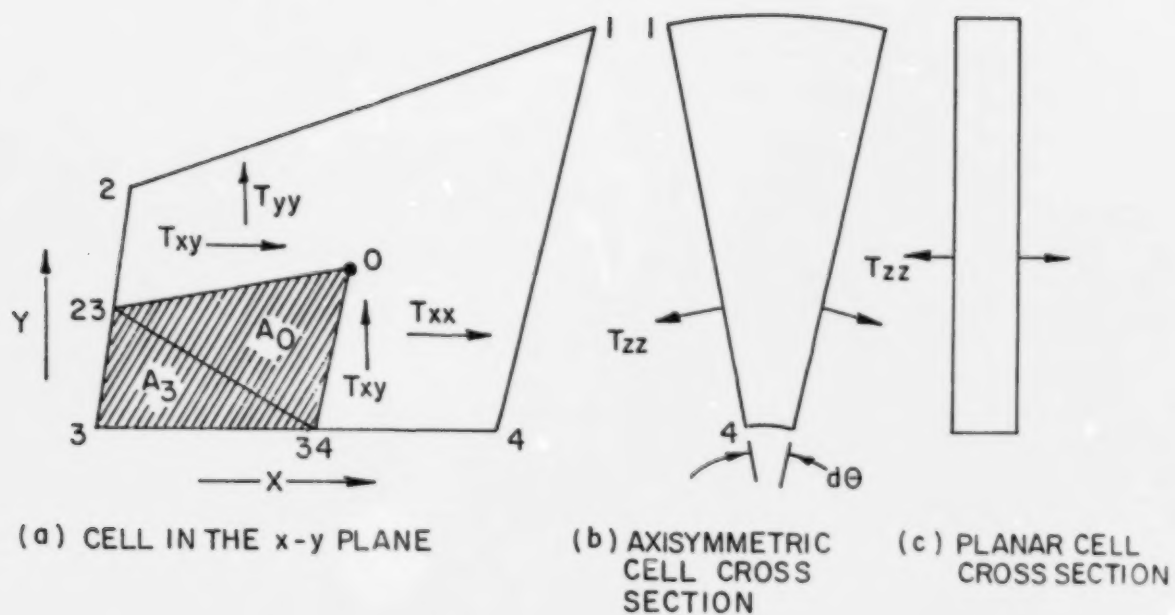


FIGURE 12: TYPICAL PORTION FOR THE COMPUTATION OF MOMENTUM

$$A_o = \frac{1}{8} [(2X_o - X_3)(Y_2 - Y_4) + X_2(Y_3 + Y_4 - 2Y_o) + X_4(2Y_o - Y_2 - Y_3)] \quad (4.7)$$

$$A_3 = \frac{1}{8} [X_4(Y_2 - Y_3) + X_3(Y_4 - Y_2) + X_2(Y_3 - Y_4)] \quad (4.8)$$

$$A_{xy} = A_o + A_3 \quad (4.9)$$

The forces in the x and y directions are as follows:

$$F_x = T_{xy} A_{yy} + T_{xx} A_{xy} \quad (4.10)$$

$$F_y = T_{yy} A_{yy} + T_{xy} A_{xx} - T_{zz} A_{xy} d\theta \quad (4.11)$$

for the axisymmetric case

or

$$F_y = T_{yy} A_{yy} + T_{xy} A_{xx} \quad (4.12)$$

for the planar case.

The mass of the small element is determined as:

$$M = \rho \frac{d\theta}{3} [A_o(Y_o + Y_3 + \frac{Y_2 + Y_4}{2}) + A_3(\frac{Y_2 + Y_4}{2} + 2Y_3)] \quad (4.13)$$

for the axisymmetric case and

$$M = \rho A_{xy} \quad (4.14)$$

for the planar case.



To obtain the change in velocity Newton's second law is applied;

$$\Delta \dot{X} = \dot{X}_{n+1/2} - \dot{X}_{n-1/2} = \frac{\left( \sum_{i=1}^4 F_{xi} \right) \Delta t_n}{\sum_{i=1}^4 M_i} \quad (4.15)$$

$$\Delta y = \dot{Y}_{n+1/2} - \dot{Y}_{n-1/2} = \frac{\left( \sum_{i=1}^4 F_{yi} \right) \Delta t_n}{\sum_{i=1}^4 M_i} \quad (4.16)$$

With regards to the strains it is assumed that they are uniform throughout the quadrilateral cell. The following equations must be met.

$$\epsilon_x + \epsilon_y = \frac{\Delta A}{A} \quad (4.17)$$

$$\epsilon_x + \epsilon_y + \epsilon_z = \frac{\Delta V}{V} \quad (4.18)$$

where  $\epsilon_x, \epsilon_y, \epsilon_z$  are changes in the strain which occur during a time step

$\Delta A$  is the change in the cell area in the x-y plane

$\Delta V$  is the change in the volume of the cell

$V$  is the volume of the cell at the beginning of the time increment.

To ensure that compatibility is enforced the following velocity field is assumed.

$$U = U_o + U_x X + U_y Y \quad (4.19)$$

$$V = V_o + V_x X + V_y Y \quad (4.20)$$

where  $U, V$  are particle velocities in the  $x, y$  directions.

Therefore

$$\epsilon_x = \frac{\partial U}{\partial X} = U_x \quad (4.21)$$

$$\epsilon_y = \frac{\partial V}{\partial Y} = V_y \quad (4.22)$$

$$\epsilon_{xy} = \frac{\partial V}{\partial X} + \frac{\partial U}{\partial Y} = V_x + U_y \quad (4.23)$$

$$\dot{w}_{xy} = \frac{1}{2} \left( \frac{\partial V}{\partial X} - \frac{\partial U}{\partial Y} \right) = \frac{1}{2} (V_x - U_y) \quad (4.24)$$

where  $\epsilon_{xy}$  = tensor shear strain rate  
 $\dot{w}_{xy}$  = rotation rate in  $x$ - $y$  plane

The parameters  $U_o$ ,  $U_x$ ,  $U_y$  can be determined for any triangle if the velocities at the coordinate points are known. For the element of Figure 12a for element 1 equation 4.19 yields.

$$U_1 = U_o + U_x X_1 + U_y Y_1 \quad (4.25)$$

$$U_2 = U_o + U_x X_2 + U_y Y_2$$

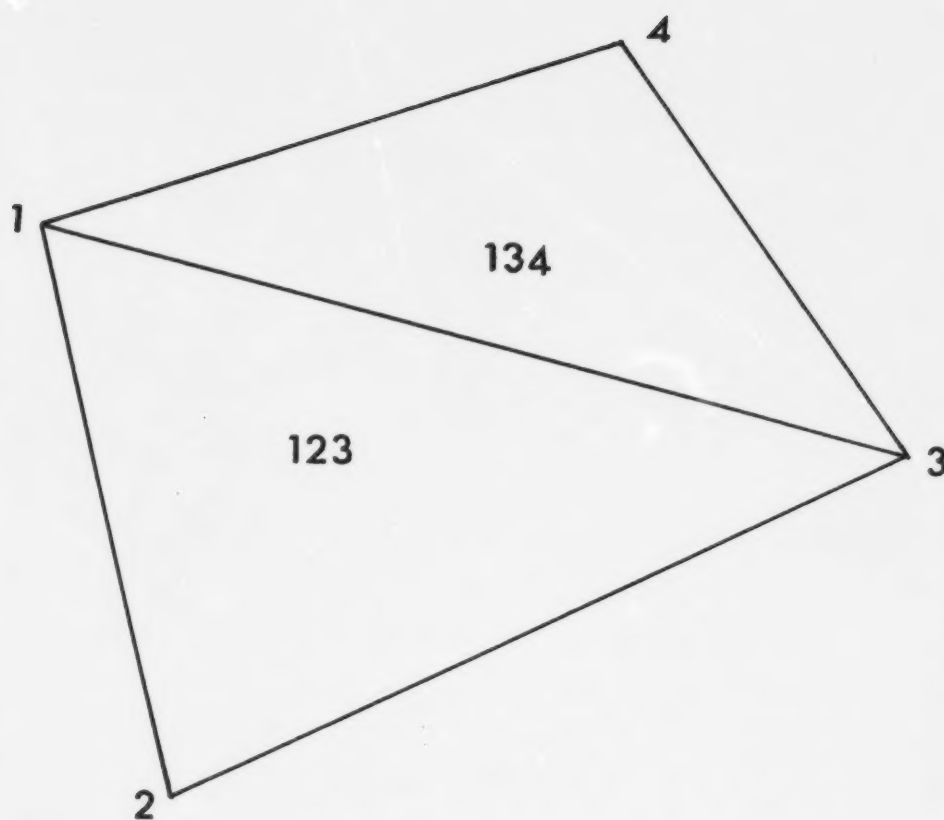


FIGURE 12a : QUADRILATERAL ELEMENT DIVIDED IN TWO TRIANGLES

$$U_3 = U_0 + U_x X_3 + U_y Y_3$$

where  $X_1, Y_1, X_2, Y_2, X_3, Y_3$  are the coordinates at points 1,2,3 (Figure 12a) at some time. The system of equations (4.25) yields the following solution.

$$U_x = \frac{(U_1 - U_2)(Y_1 - Y_3) - (U_1 - U_3)(Y_1 - Y_2)}{2[(X_1 - X_2)(Y_1 - Y_3) - (X_1 - X_3)(Y_1 - Y_2)]} \quad (4.26)$$

$$U_y = -\frac{(U_1 - U_3)(X_1 - X_3) - (U_1 - U_2)(X_1 - X_2)}{2[(X_1 - X_2)(Y_1 - Y_3) - (X_1 - X_3)(Y_1 - Y_2)]} \quad (4.27)$$

For the velocity  $V$  similarly

$$V_1 = V_0 + V_x X_1 + V_y Y_1$$

$$V_2 = V_0 + V_x X_2 + V_y Y_2 \quad (4.28)$$

$$V_3 = V_0 + V_x X_3 + V_y Y_3$$

with a solution

$$V_x = \frac{(V_1 - V_2)(Y_1 - Y_3) - (V_1 - V_3)(Y_1 - Y_2)}{2[(X_1 - X_2)(Y_1 - Y_3) - (X_1 - X_3)(Y_1 - Y_2)]} \quad (4.29)$$

$$V_y = -\frac{(V_1 - V_3)(X_1 - X_3) - (V_1 - V_2)(X_1 - X_2)}{2[(X_1 - X_2)(Y_1 - Y_3) - (X_1 - X_3)(Y_1 - Y_2)]} \quad (4.30)$$

Moreover

$$A = [(X_1 - X_2)(Y_1 - Y_2) - (X_1 - X_3)(Y_1 - Y_2)] \quad (4.31)$$

where  $A$  is the area of the triangle 123.

Equation (4.21) has to be satisfied. The calculation is performed in two steps. First the condition has to be satisfied for each of the triangles the quadrilateral is divided into and then the condition for the whole quadrilateral has to be satisfied.

Let

$$A = \frac{1}{2} (A^0 + A^1) \quad (4.32)$$

where  $A^0, A^1$  are the areas of the triangle 123 at the beginning and at the end of the time step. The strain rate can be expressed as:

$$\dot{\epsilon}_x = \frac{A^0 U_x^0 + A^1 U_x^1}{A^0 + A^1} \quad (4.33)$$

$$\dot{\epsilon}_y = \frac{A^0 V_y^0 + A^1 V_y^1}{A^0 + A^1} \quad (4.34)$$

where the values with subscript 0 are computed with initial values of  $x$  and  $y$  and values with superscript 1 are the final values of  $x$  and  $y$ . The final values of the coordinates can be expressed as:

$$x_i^1 = x_i^0 + U_i \Delta t \quad (4.35)$$

$$y_i^1 = y_i^0 + V_i \Delta t \quad (4.36)$$

It will be proved that the expression (4.33) is exactly compatible with the expression (4.17) where the definition of the strain was given. Equation (4.17) can be written as:

$$(\dot{\epsilon}_x + \dot{\epsilon}_y) \Delta t = \frac{A^1 - A^0}{1/2(A^1 + A^0)} \quad (4.37)$$

where the values with superscripts 0 and 1 are calculated before and after the time step  $\Delta t$ .

$$(\dot{\epsilon}_x + \dot{\epsilon}_y) \Delta t = \left( \frac{\Delta t}{A^0 + A^1} \right) [A^0(U_x^0 + V_y^0) + A^1(U_x^1 + V_y^1)] \quad (4.38)$$

(4.38) because of (4.26), (4.27), (4.29), (4.30) and (4.31) yields

$$\begin{aligned} (\dot{\epsilon}_x + \dot{\epsilon}_y) \Delta t &= \\ \frac{\Delta t}{A^0 + A^1} & \left[ A^0 \frac{(U_1 - U_2)(Y_1^0 - Y_3^0) - (U_1 - U_3)(Y_1^0 - Y_2^0) + (V_1 - V_3)(X_1^0 - X_2^0) - (V_1 - V_2)(X_1^0 - X_3^0)}{2A^0} \right. \\ & + A^1 \frac{(U_1 - U_2)(Y_1^0 - Y_3^2 + (V_1 - V_3)\Delta t) - (U_1 - U_3)(Y_1^0 - Y_2^2 + (V_1 - V_2)\Delta t)}{2A^0} \\ & \left. + A^1 \frac{(V_1 - V_3)(X_1^0 - X_2^0 + (U_1 - U_2)\Delta t) - (V_1 - V_2)(X_1^0 - X_3^0 + (U_1 - U_3)\Delta t)}{2A^1} \right] \\ &= \frac{\Delta t}{2(A^0 + A^1)} [2(U_1 - U_2)(Y_1^0 - Y_3^0) - 2(U_1 - U_3)(Y_1^0 - Y_2^0) + 2(V_1 - V_3)(X_1^0 - X_2^0) \end{aligned}$$

$$\begin{aligned}
& - 2 (v_1 - v_2)(x_1^0 - x_3^0) + 2(v_1 - v_3)(u_1 - u_2)\Delta t - 2(v_1 - v_2)(u_1 - u_3)\Delta t] \\
& = \frac{\Delta t}{A^0 + A^1} [(u_1 - u_2)(y_1^0 - y_3^0) - (u_1 - u_3)(y_1^0 - y_2^0) + (v_1 - v_3)(x_1^0 - x_2^0) \\
& - (v_1 - v_2)(x_1^0 - x_3^0) + (v_1 - v_3)(u_1 - u_2)\Delta t - (v_1 - v_2)(u_1 - u_3)\Delta t] \quad (4.39)
\end{aligned}$$

Moreover

$$\begin{aligned}
& \frac{A^1 - A^0}{1/2(A^1 + A^0)} = \frac{2(A^1 - A^0)}{A^1 + A^0} = \\
& \frac{2}{A^1 + A^0} \left[ \frac{1}{2} [(x_1^1 - x_1^0)(y_1^1 - y_3^1) - (x_1^1 - x_3^1)(y_1^1 - y_2^1)] - \right. \\
& \left. \frac{1}{2} [(x_1^0 - x_2^0)(y_1^0 - y_3^0) - (x_1^0 - x_3^0)(y_1^0 - y_2^0)] \right] = \\
& \frac{1}{A^1 + A^0} \left[ (x_1^0 - x_2^0 - (u_1 - u_2)\Delta t)(y_1^0 - y_3^0 + (v_1 - v_3)\Delta t) - \right. \\
& \quad (x_1^0 - x_3^0 + (u_1 - u_3)\Delta t)(y_1^0 - y_2^0 + (v_1 - v_2)\Delta t) - \\
& \quad \left. (x_1^0 - x_2^0)(y_1^0 - y_3^0) + (x_1^0 - x_3^0)(y_1^0 - y_2^0) \right] \\
& = \frac{1}{A^1 + A^0} [(x_1^0 - x_2^0)(v_1 - v_3)\Delta t + (u_1 - u_2)(y_1^0 - y_3^0)\Delta t + \\
& \quad - (y_1^0 - y_2^0)(u_1 - u_3)\Delta t + (v_1 - v_3)(u_1 - u_3)(\Delta t)^2 -
\end{aligned}$$



$$\begin{aligned}
 & (V_1 - V_2)(U_1 - U_3) \Delta t^2 = \\
 & \frac{\Delta t}{A_0 + A_1} [(U_1 - U_2)(Y_1^0 - Y_3^0) - (U_1 - U_3)(Y_1^0 - Y_2^0) + (V_1 - V_3)(X_1^0 - X_2^0) \\
 & - (V_1 - V_2)(X_1 - X_3^0) + (V_1 - V_3)(U_1 - U_2) \Delta t - (V_1 - V_2)(U_1 - U_3) \Delta t] \\
 & \quad \quad \quad (4.40)
 \end{aligned}$$

From (4.39) and (4.40) it follows that (4.37) is satisfied exactly indicating that the equations (4.33), (4.34) meet the first compatibility requirement.

For the quadrilateral calculation the strain rate can be expressed as:

$$\dot{\epsilon}_x = \frac{A_{123}^0 U_{123x}^0 + A_{123}^1 U_{123x}^1 + A_{134}^0 U_{134x}^0 + A_{134}^1 U_{134x}^1}{A_{123}^0 + A_{123}^1 + A_{134}^0 + A_{134}^1} \quad (4.41)$$

where subscript 123 refers to triangle 123 and subscript 134 refers to triangle 134.

By following the same procedure as before it can be shown that:

$$(\dot{\epsilon}_x + \dot{\epsilon}_y) \Delta t = \frac{A_{123}^1 + A_{134}^1 - A_{123}^0 - A_{134}^0}{1/2(A_{123}^1 + A_{134}^1 + A_{123}^0 + A_{134}^0)} \quad (4.42)$$

The requirement of equation 4.18 is met in the following way:

The mass in the case of the axisymmetric cell is:

$$M = \int \frac{d\theta}{3} \rho \sum_i A_i \sum_j Y_{ij} = \frac{2\pi\rho}{3} \sum_i A_i \sum_j Y_{ij} \quad (4.43)$$

where  $A_i$  is the area of the triangle  $i$  on the  $x$ - $y$  plane,  
 $y_{ij}$  are the radial positions of the vertices of  
 triangle  $i$  and  
 $\rho$  is the density

For planar cells

$$M = \rho A_{xy} \quad (4.44)$$

where  $\rho$  is the density and  
 $A_{xy}$  the area of the element on the  $x$ - $y$  plane.

Since the mass is conserved the density in each cycle can be calculated from equations (4.43) and (4.44).

The relative volume in equation (4.18) is

$$\frac{\Delta V}{V} = \frac{2 (\rho_1 - \rho_2)}{\rho_1 + \rho_2} \quad (4.45)$$

where  $\rho_1$  and  $\rho_2$  are densities before and after the time step  $\Delta t$ . With  $\dot{\epsilon}_x$ ,  $\dot{\epsilon}_y$ ,  $\frac{\Delta V}{V}$  known  $\dot{\epsilon}_z$  is selected so that

$$\dot{\epsilon}_z \Delta t = \frac{\Delta V}{V} - (\dot{\epsilon}_x + \dot{\epsilon}_y) \Delta t \quad (4.46)$$

Equation (4.46) guarantees that equation (4.18) is satisfied.

The conservation of energy equation is expressed as:

$$E^1 = E^0 + V \sum_{ij} \sigma_{ij} d\epsilon_{ij} \quad (4.47)$$

where  $E_1, E^0$  are the internal energies at the end and the beginning of the time increment.

$V$  is the specific volume

$\sigma_{ij}$  is the stress and

$\epsilon_{ij}$  is the strain value at point  $ij$ .

The energy is calculated twice in the program. The first calculation follows the calculation of density and strain and the stresses are those of the previous step. Then the stresses are computed based on the calculation and the energy is calculated again. The values of the energy which were obtained by the second calculation are stored so that they are used in the next cycle of calculations. Analytically the initial calculation is based on the following equation:

$$E = E_0 + V (\sigma_{xx0}^1 \Delta\epsilon_x + \sigma_{yy0}^1 \Delta\epsilon_y + \sigma_{zz0}^1 \Delta\epsilon_z + 2 \sigma_{xy0}^1 \Delta\epsilon_{xy}) - (P_0 + Q) (V - V_0) \quad (4.48)$$

where  $\sigma_{xx0}^1, \sigma_{yy0}^1, \sigma_{zz0}^1, \sigma_{xy0}^1$  are stresses from the previous time increment  
 $Q$  is the artificial viscosity the physical meaning of which will be explained later in the chapter.  
 $P_0$  is the pressure of the previous time step  
 $V$  is the volume of the cell.

The energy calculation is repeated after the stress calculation. In this case

$$\int \sigma_{ij} d\epsilon_{ij} = \frac{\sigma_{ij1} + \sigma_{ij0}}{2} \Delta\epsilon_{ij}$$

where subscript 1 denotes values of the end of the time interval and subscript 0 values at the beginning. Then equation 4.47 gives

$$\begin{aligned} E = E_1 + V & \left[ \frac{\sigma_{xx1} + \sigma_{xx0}}{2} \Delta\epsilon_x + \frac{\sigma_{yy1} + \sigma_{yy0}}{2} \Delta\epsilon_y + \right. \\ & + \left. \frac{\sigma_{zz1} + \sigma_{zz0}}{2} \Delta\epsilon_z + (\sigma_{xy1} + \sigma_{xy0}) \Delta\epsilon_{xy} \right] - \\ & \left( \frac{P + P_0}{2} + Q \right) (V - V_0) \end{aligned} \quad (4.49)$$

#### 4.1.2 The Artificial Viscosity

The different equations together with an equation of state lead to cell quantities that follow an adiabat. However shock waves are producing entropy so that over the thickness of the shock the kinetic energy of the short wave lengths is transferred to thermal energy. Therefore without some dissipative mechanism, energy and momentum jump conditions cannot be satisfied at the same time at the shock front. Energy is distilled into the short wave lengths on a difference mesh. Therefore, significant oscillation in the cell quantities will occur after the passage of the shock wave.

In view of this problem an artificial viscous stress is commonly used in the finite difference wave propagation calculations. Thus all the shocks are broadened on the difference mesh and the entire flow field can be treated by the conservation equations of continuous flow.

In the computer program the linear and quadratic forms of artificial viscosity are provided. Both are related to the rate of compression of the material. When the material is expanding the artificial viscosity is zero. The linear form of artificial viscosity can be expressed as:

$$Q_1 = C_1 C_s A \frac{\Delta \rho}{\Delta t} \quad (4.50)$$

where  $C_1$  is the coefficient of linear artificial viscosity ( $0.05 < C < 0.5$ )  
 $C_s$  is the sound speed of the material  
 $A$  is the area of the cell (x-y plane)  
 $\Delta \rho$  is the change in density over the time step  $\Delta t$ .

The quadratic form can be expressed as

$$Q_2 = \frac{C_o^2 A}{\rho} \left( \frac{\Delta \rho}{\Delta t} \right)^2 \quad (4.51)$$

with  $C_o$  the coefficient of quadratic artificial viscosity ( $C_o = 4.0$ )

The artificial stress  $Q$  is:

$$Q = Q_1 + Q_2 \quad (4.52)$$

where  $Q_1$  is the stress due to the linear artificial viscosity and  
 $Q_2$  is the stress due to the quadratic artificial viscosity

#### 4.1.3 The Constitutive Model

In the computer program the stress tensor is separated into a pressure and a deviator tensor. The pressure is the average stress

$$P = \frac{1}{3} \sum_i \sigma_{ij} \quad (4.53)$$

The stress deviator elements are

$$\sigma'_{ij} = \sigma_{ij} - P\delta_{ij}$$

where  $\sigma_{ij}$  are stress tensor elements and  $\delta_{ij}$  is the Kronecker delta. The pressure is given as a function of the internal energy, the density and the mass fraction of the solid components in the material. It is normally computed from the HOM equation of state. For explosive materials the mass fraction of the undecomposed explosive must be calculated at each time step. This is done by various techniques which have been incorporated in the Program.

##### a. Forest Fire

The Forest Fire technique was analysed in the previous chapter. In the computer code the rate is programmed as a function of pressure. The logarithm of the rate is generally expressed as:

$$\ln(\text{rate}) = A_1 + A_2 P t \dots + A_n P^{n-1} \quad (4.54)$$

where  $\text{rate} = -\frac{1}{W} \frac{dW}{dt}$  with  $W$  the mass fraction of

unreacted explosive and  $t$  the time

and  $P$  is the pressure

Normally the logarithm of the rate is fitted to a polynomial of the pressure for different pressure ranges in order to minimize the error of the fit especially in the low pressure areas. The rate is set to zero if the pressure is less than the minimum pressure in the fit. Moreover the burning is completed above the C-J pressure.

For the Forest Fire technique to be applied the Pop plots of the explosives which will be modelled must be known. However the determination of the Pop plots is time consuming and very expensive. For this reason other burning models were included in the model.

#### b. Arrhenius Burn

The Arrhenius burn is programmed by the following equation.

$$\text{Rate} = Z e^{-E/RT} \quad (4.55)$$

where rate =  $-dW/dt$  with  $W$  the mass fraction of unreacted explosive and  $t$  the time

$Z$  is the frequency factor  
 $E$  is the activation energy  
 $R$  is the gas constant and  
 $T$  is the absolute temperature

The temperature in this case is provided by the HOM equation of state. However the values of the activation energy and the frequency factor for each particular explosive must be known. Therefore the applicability of the burn is limited to a few pure explosives for which  $E$  and  $Z$  are known.



### c. Gamma Law Taylor Wave Burn

The gamma law burn model calculates the decomposition of a burning explosive. The burning is assumed to start from a point or a line inside the explosive mass. The chemical energy to be released is stored in each high explosive zone as initial energy  $Q_0$ . The time for the detonation front to reach a specific cell is calculated in advance from the C-J point shock velocity and the distance of the middle of the cell from the point of initiation. This quantity is stored at each cell. Initially a burn fraction is calculated so as to spread the burn front over several cells. Therefore

$$W = \frac{X_1 - X_d}{r \Delta X} \quad (4.56)$$

$$0 \leq W \leq 1$$

where  $W$  is the mass fraction of unreacted explosived  
 $X_1$  is the position of the cell  
 $X_d$  is the point of initiation  
 $\Delta X$  is the grid spacing  
 $r$  is a constant to spread the burning.

Inside the explosive the burn calculations start at the moment the detontaion reaches the cell. The mass fraction of unreacted explosive is calculated as follows:

$$W^{n+1} = 1 - (t^{n+1} - t_p)D/r\Delta X \quad (4.57)$$

where  $t^{n+1}$  is the time at step  $n+1$   
 $t_p$  is the pre-calculated time for the shock front to reach the cell  
 $D$  is the detonation velcoty  
 $\Delta X$  is the grid spacing

$r$  is the constant to spread the wave.

The above formula applies for the case where  $t^{n+1} \geq t_b$ . If  $w^{n+1}$  is calculated to be less or equal to zero the reaction is assumed to be completed. Moreover if  $t^{n+1} < t_b$  the reaction has not reached the cell yet and the mass fraction of unreacted explosive is equal to 1 ( $w = 1$ ).

When the reaction is completed the reaction products are assumed to expand adiabatically following a constant gamma law.

Obviously the previous burning technique is not predictive for initiation purposes. It has been included in the model for quick calculations and in the cases where the explosive reacts ideally and the focus of interest is in the material surrounding the explosive.

## CHAPTER FIVE

### EXPERIMENTAL DETERMINATION OF INPUT DATA

#### 5.0 INTRODUCTION

As it was described in Chapter Two the Forest Fire technique was selected to describe the decomposition rate as a function of the initial applied pressure in the modelling of commercial explosives. Experimental data required to implement the technique are:

- The relationship between the initial pressure and the distance of run to detonation (Pop - plot).
- The non reactive Hugoniot of the explosive.

In the following the experimental technique which was used is presented.

#### 5.1 THE WEDGE TEST

In order to obtain Pop Plots and Hugoniot relationships for commercial explosives wedge tests were conducted. The wedge tests are named for the wedge shaped explosive which is shocked by a plane wave generator - booster - attenuator system. The explosive is wedge shaped so that the shock or detonation wave moving through it is visible along the slant face.

The slant face is usually covered with glass microballoons. Moreover the slant surface of the wedge is covered by a very thin plexiglas sheet so as to create a narrow gap between the explosives and the plexiglas. When the microballoons and the air gap are compressed suddenly they flash

brightly. A streak camera is set up with the slit parallel to the base of the wedge. The experimental technique is shown in Figure 13. A typical streak record from a wedge experiment is shown in Figure 14.

The shock which enters the wedge must have a high degree of planarity so that the point at which the shock wave becomes a detonation wave can be located. Moreover the planarity of the wave which impacts the wedge affects the measurement of the shock velocities before and after the detonation. For those reasons the shock which impacts the wedge must be produced by an accurate plane wave generator.

The system consists of a 12.7 cm plane wave generator, a pentolite (50% RDX, 50% TNT) booster, a plexiglas attenuator of varying thickness and an explosive wedge. The wedge is placed at the centre of the attenuator plate in order to avoid edge effects which will affect the planarity of the wave at the sides.

## 5.2 THE PLANE WAVE GENERATOR

The plane wave generator which was developed is a binary explosive lens consisting of an explosive of higher detonation velocity,  $D_1$ , surrounding an explosive of a lower detonation velocity  $D_2$ . A cross section of a plane wave generator parallel to its vertical axis is shown in Figure 15. A cross section normal to the vertical axis is shown in Figure 16. The inside of the cone is filled with the explosive detonating at a lower velocity and the remainder of the generator is filled with the explosive detonating at a higher velocity. The geometry is chosen so that the high velocity detonation travelling along the surface of the cone initiates a detonation in the inner explosive which just keeps pace with the outer one. Therefore the angle is chosen such that:

$$D_2 = D_1 \sin \alpha \quad (5.1)$$

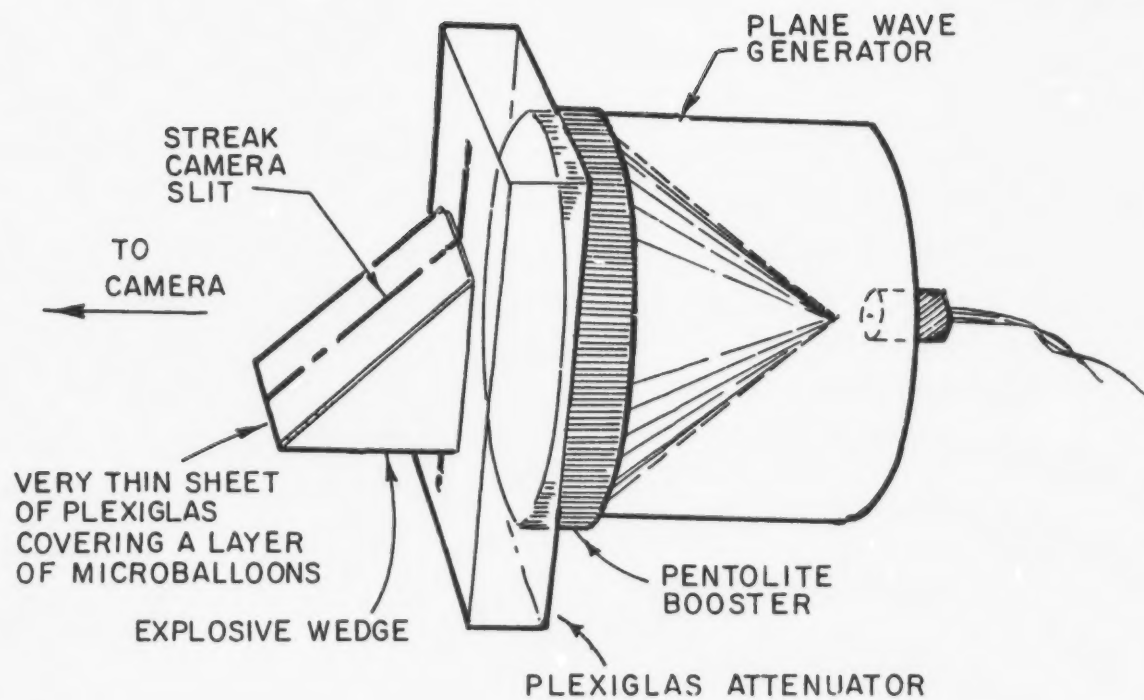


FIGURE 13: EXPERIMENTAL SET UP FOR WEDGE TESTS

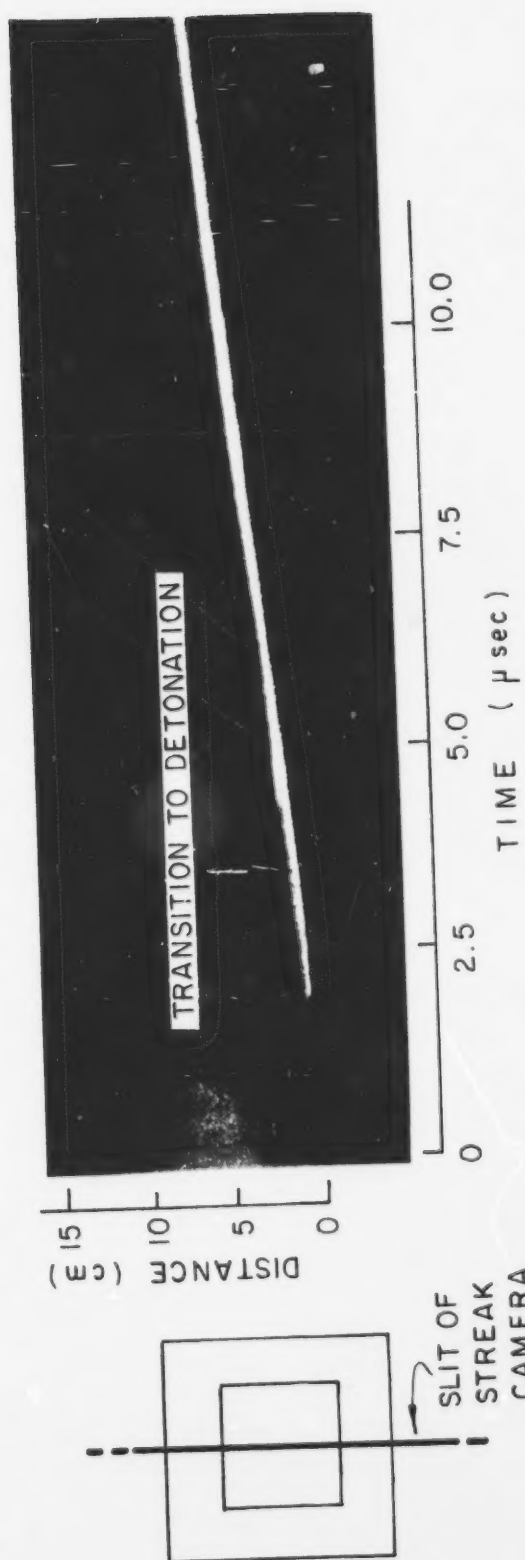


FIGURE 14: TYPICAL STREAK CAMERA RECORD

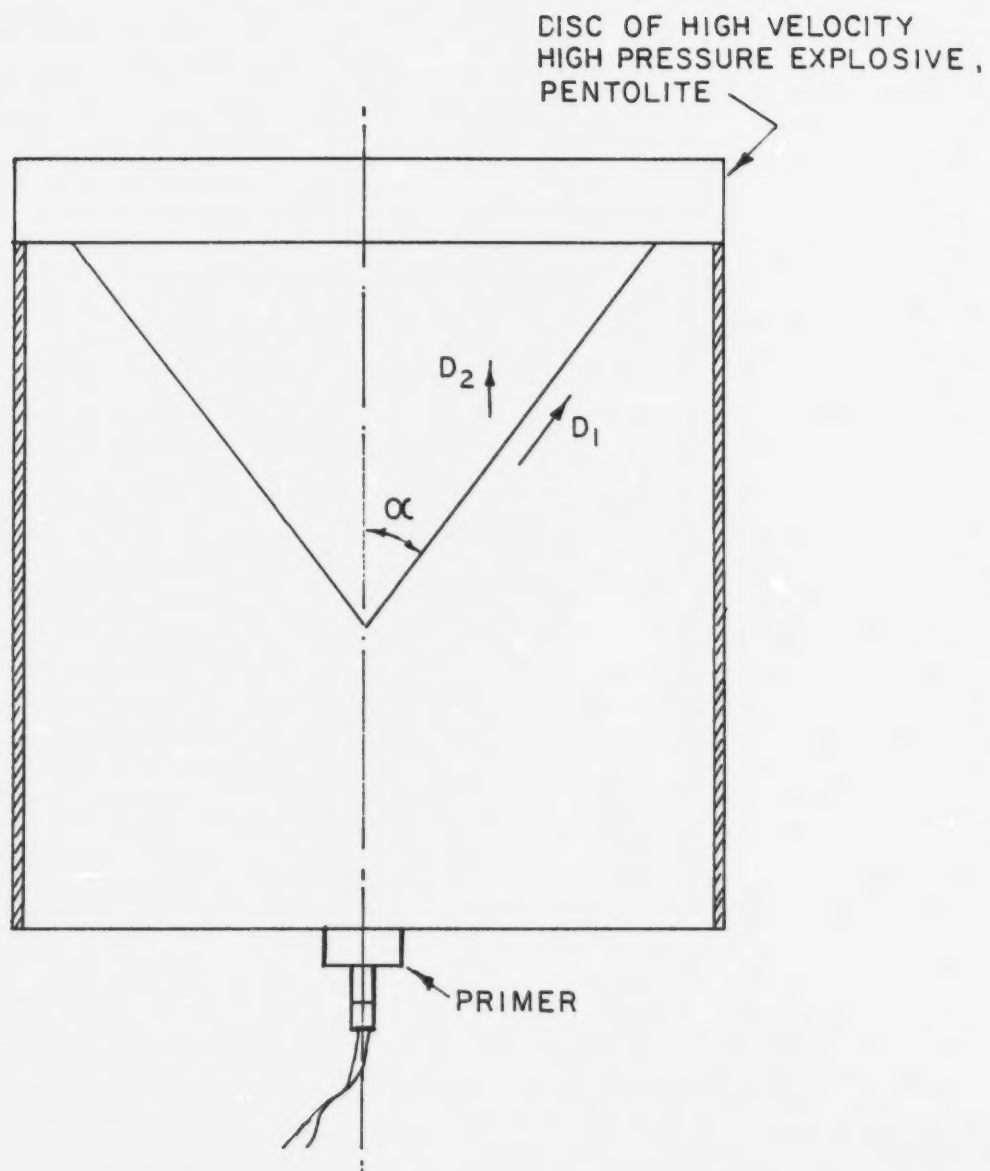


FIGURE 15: SECTION OF A PLANE WAVE GENERATOR



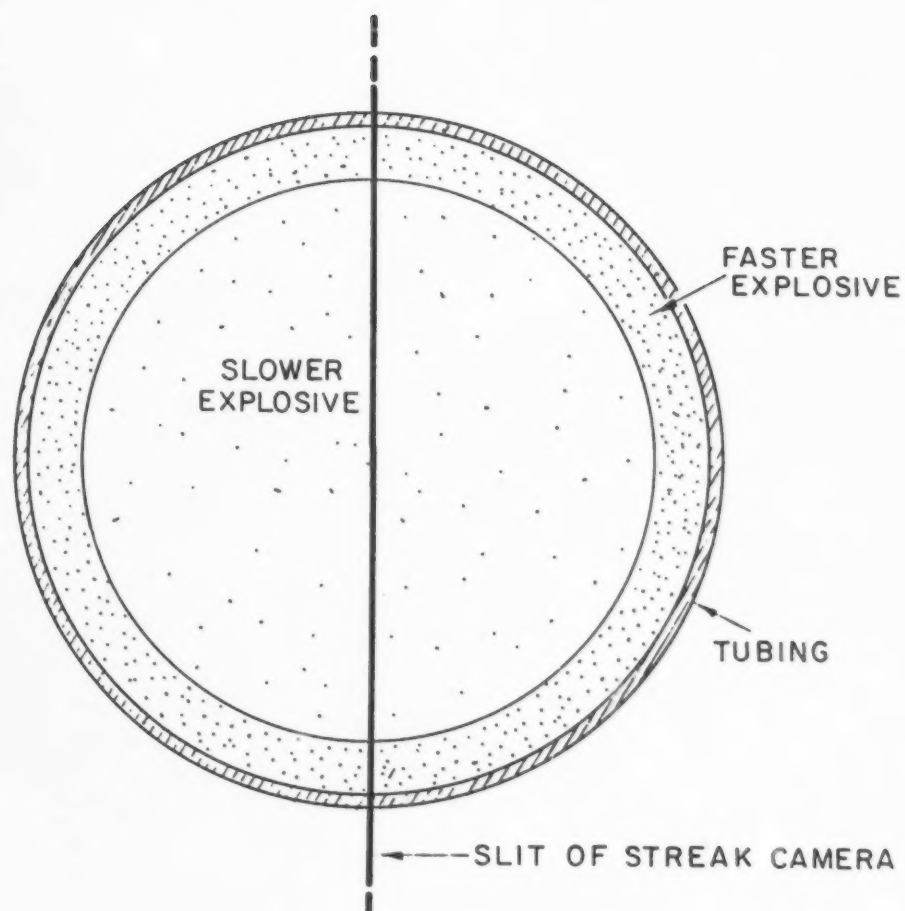


FIGURE 16: CROSS SECTION NORMAL TO THE VERTICAL AXIS OF A PLANE WAVE GENERATOR

On the basis of this principle two plane wave generators were developed.

In the first type powered TNT and powdered tetryl were used. The bulk densities of these explosives are 0.94 g/cc for the TNT and 1.06 g/cc for the tetryl. The velocity of detonation of TNT and tetryl at these densities are 4870 m/s and 5850 m/sec respectively. From these detonation velocities an angle of  $33.6^\circ$  is calculated from equation (5.1). Therefore the angle of the cone is  $67^\circ$ . The shell for the tetryl and the TNT consisted of a 15.3 cm i.d., 15.3 cm long piece of PVC tubing. The plane wave generators were made hand pressed. The tetryl was initiated at the centre of the top of the generator by an 8 g detaprime and electric blasting cap. However since tetryl is highly toxic and not readily available, a second type of plane wave generator was developed. This consisted of a TNT cone surrounded by RDX.

The densities of powdered TNT and powdered RDX are 0.94 g/cc and 0.90 g/cc respectively. The corresponding velocities of detonation are 4870 m/s for TNT and 5720 m/s for RDX. However the generator designed on the basis of the above did not produce a plane wave, probably because of the short length of the generator. By changing the angle of the cone and the density of TNT a plane wave generator was obtained.

The plane wave generator consisted of powdered TNT mixed with 0.8% microballoons ( $\rho = 0.1$  g/cc) to obtain a density of 0.87 g/cc in the cone and powdered RDX of a density of 0.90 g/cc. The angle of the cone was  $56^\circ$  ( $\alpha = 28^\circ$ ).

The accuracy of the plane wave generators was satisfactory. Over a diameter of 12.7 cm (5") the deviations from the simultaneous arrivals of the detonation waves at the surface of the generator were less than  $\pm 0.2 \mu\text{s}$ . A typical streak camera record showing the planarity of the plane wave generators is shown in Figure 17. In this figure the slit of the

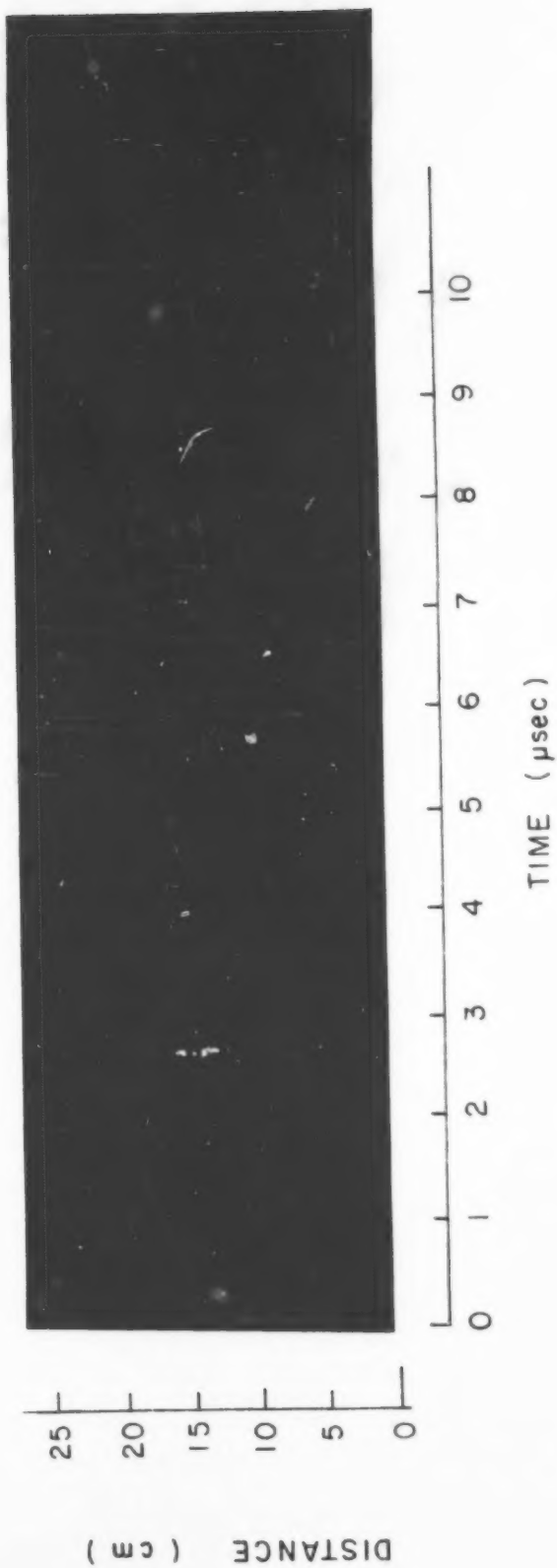


FIGURE 17 : TYPICAL STREAK CAMERA RECORD OF THE EMERGING DETONATION WAVE FROM A 15.3 CM (6")  
PISTON PLANE WAVE GENERATOR

streak camera is aligned parallel to a diameter of the front face of the plane wave generator.

### 5.3 THE STREAK CAMERA

The streak camera used in the wedge tests is a simultaneous streak and framing camera made by Cordin (model 200). The camera is shown in Figures 18 and 19. Both the framing and streak records are obtained simultaneously through the same objective lens and by using a single rotating mirror.

The optical paths of the two systems are separated in space so that the two systems are served at the same time. The rotating mirror is made of highly polished steel and is driven by compressed nitrogen.

The objective lens is a Nikon 200-600 mm zoom lens (f-9.0).

Synchronization and control are accomplished by a set of control units which consist of operating controls, interlock relays and an electronic system controlling synchronization. The rotating mirror signal is amplified and gated so that upon pressing the firing button, the synchronization control unit produces a trigger pulse to initiate the event under study.

A typical streak camera record is represented in Figure 20. The shock velocity at each point of the record can be calculated by the following formula.

$$U_s = R.M.W. \tan \theta \quad (5.2)$$

where  $U_s$  is the shock velocity  
 $R$  is the reduction factor obtained by a scale

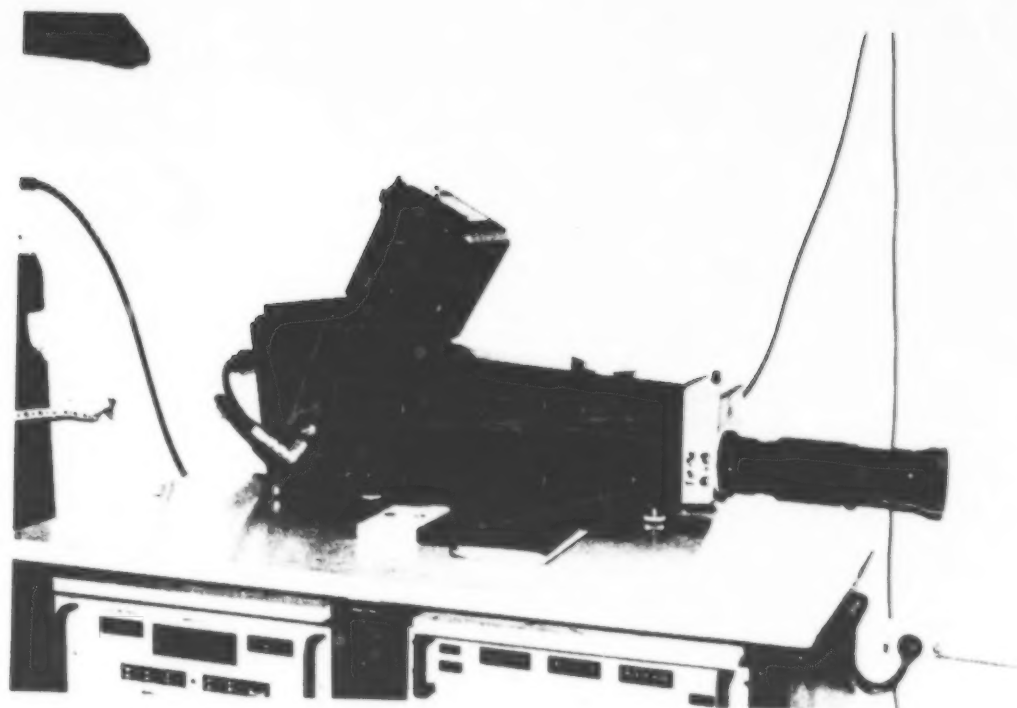


FIGURE 18 SIMULTANEOUS STREAK AND FRAMING CAMERA

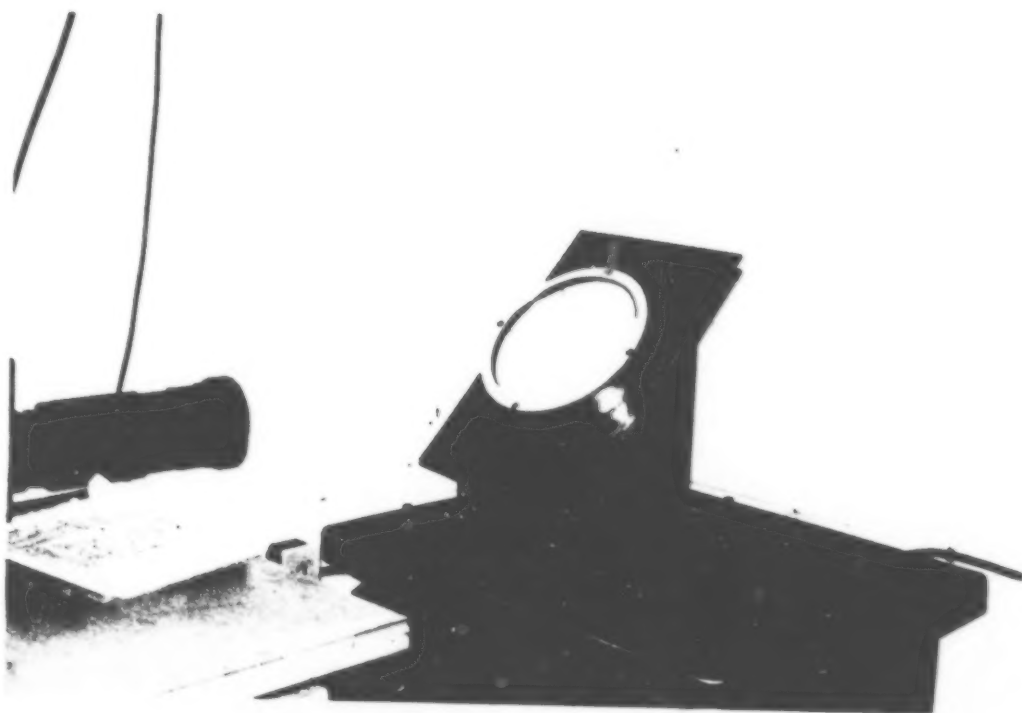


FIGURE 19 : CAMERA LENS AND ONE OF THE TWO PERISCOPE MIRRORS USED IN THE WEDGE SHOTS

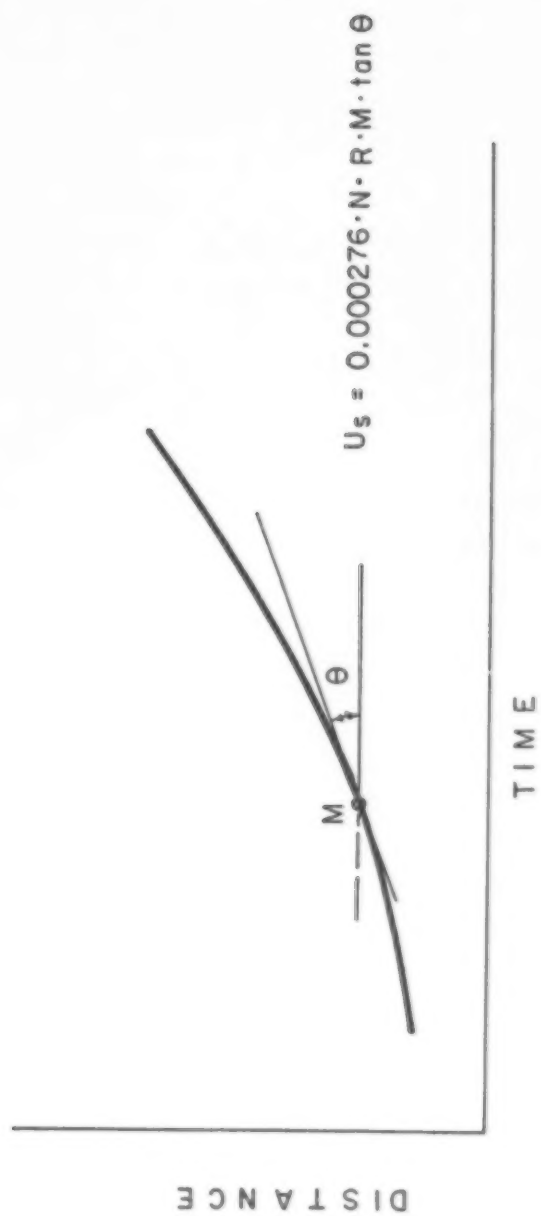


FIGURE 20 : REPRESENTATION OF A TYPICAL STREAK CAMERA RECORD

photographed at the same spot as the charge prior to the experiment (static image)

$W$  is the writing speed of the camera

$\theta$  is the angle between the tangent to the record and the line perpendicular to the line of the slit of the camera.

The writing rate of the camera can be expressed by the formula

$$W = 4 \pi N R \quad (5.3)$$

where

$W$  is the writing rate (mm/ $\mu$ s)

$N$  is the mirror frequency (revolution/s)

$R$  is the distance from the centre of rotation to the mirror to the film. For the camera used in the tests  $R = 220$  mm. The factor

Therefore the writing speed for the camera which was used is:

$$W = 4 \pi R N = 0.002764 N \quad (5.4)$$

The mirror period is provided by the electronic controls of the camera and is known accurately.

The tangent angle is very important in the calculation. Generally the accuracy of the angle  $\theta$  is not better than  $0.25^\circ$ .

#### 5.4 DETERMINATION OF THE RELATIONSHIP BETWEEN PLEXIGLAS THICKNESS AND PLEXIGLAS SHOCK VELOCITY

In order to calculate the initial pressure of the shock wave impacting the wedge, the Hugoniot of the plexiglas and the



relationship between the shock velocity in the plexiglas and the thickness of the plexiglas must be known.

The Hugoniot of the Plexiglass attenuator is accurately known from the work of various investigators (7,20).

In order to obtain the relationships between the thickness of the plexiglas attenuator and the shock velocity in the plexiglas at the conditions under which a wedge test is performed the shock velocity was measured continuously in thick plexiglas wafers which are impacted by the same plane wave generator/booster system which was used at the wedge experiments. The experimental set up is shown in Figure 21. The experiment is photographed by having the slit of the streak camera aligned parallel to the axis of the charge. When the shock wave enters the attenuator it produces a cut-off of the light transmitted through the plexiglas. The cut-off produces a well defined photographic record of the shock travelling through the plexiglas. Figure 22 gives a typical streak camera record for the measurement of the shock velocity in the plexiglas wafer.

Two experiments of this kind were conducted. In the experiments the thickness of the attenuator was 10.2 cm. It was observed that the shock velocity is rapidly attenuated in the plexiglas dropping off to a level of 3400 m/sec after 10 cm. In another experiment involving a 20 cm thick wafer it was observed that at 20 cm the shock velocity was 2500 m/s which is very close to the sound speed of plexiglas (2200 - 2400 m/sec.) The results are shown in Figure 23.

### 5.5 SOUND VELOCITY MEASUREMENT

The Hugoniot for most materials can be expressed by the relationship:

$$U_s = C + K U_p \quad (5.5)$$

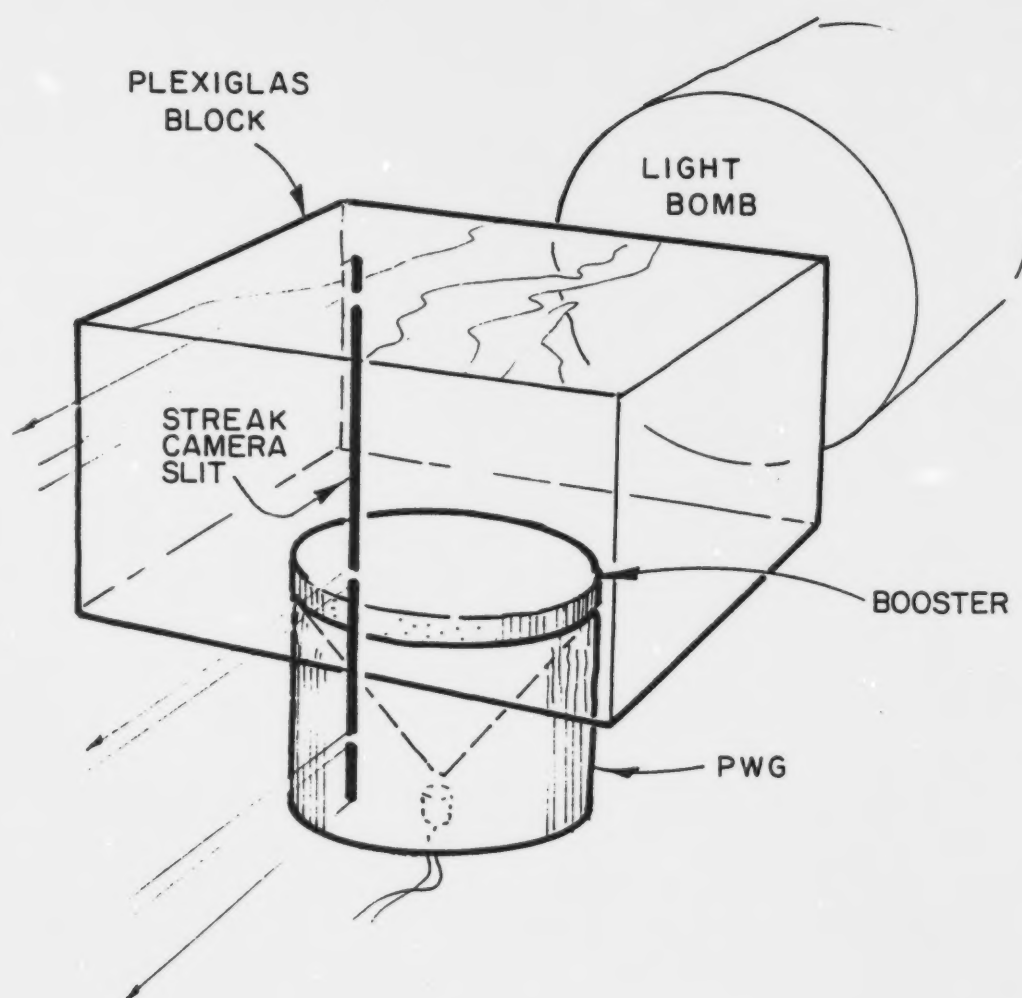


FIGURE 21: EXPERIMENTAL ARRANGEMENT FOR THE MEASUREMENT OF THE SHOCK VELOCITY IN THE PLEXIGLAS ATTENUATOR.

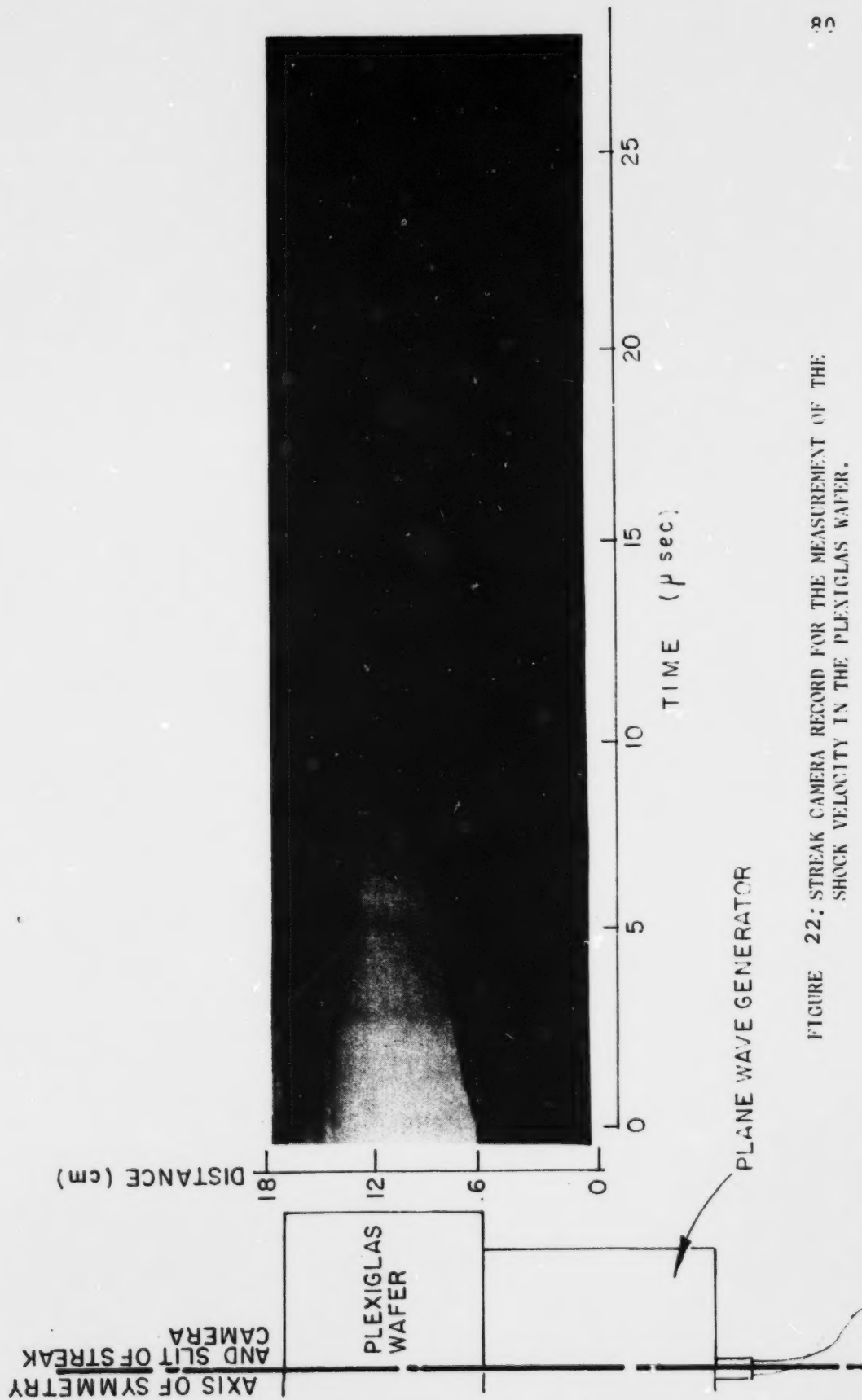


FIGURE 22: STREAK CAMERA RECORD FOR THE MEASUREMENT OF THE SHOCK VELOCITY IN THE PLEXIGLAS WAFER.

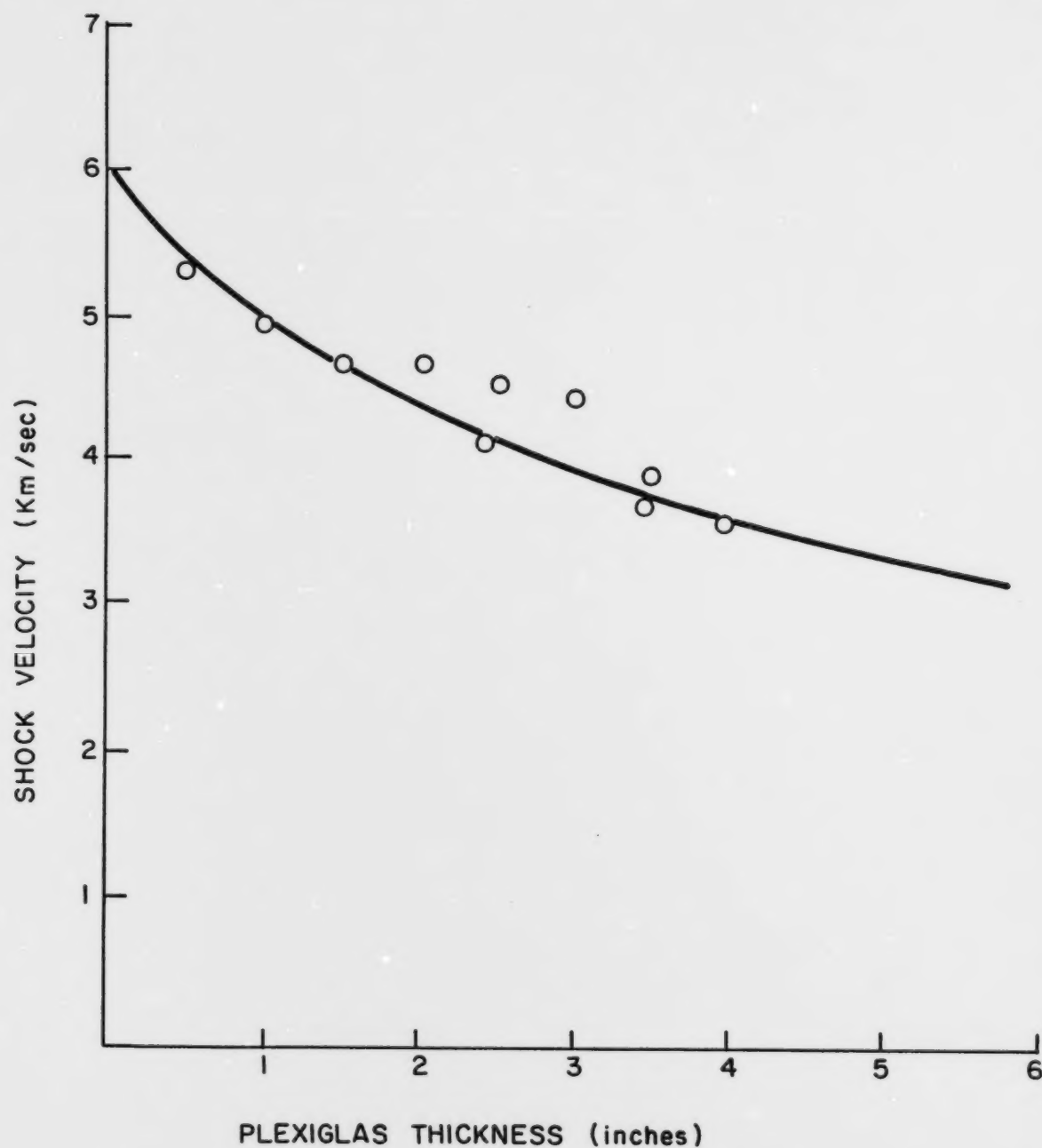


FIGURE 23: RELATIONSHIP BETWEEN SHOCK VELOCITY VS. THICKNESS OF PLEXIGLAS BLOCK FOR THE PLANE WAVE GENERATORS USED IN THE POP PLOT DETERMINATIONS

where  $U_s$  is the shock velocity  
 $U_p$  is the particle velocity  
 $C$  is the sound speed and  
 $S$  is a constant.

The constant  $C$  can be found by the fit of the experimental  $U_s$ ,  $U_p$  data. However a measured sound speed can be used to provide an extra point on the  $U_s$ ,  $U_p$  relationship.

The experimental set up is shown in Figure 23. It consists of an ultrasonic pulsing system (PUNDIT by CNS Electronics) a transducer-receiver system and a digital oscilloscope (HAMEG). The pulse from the pulsing system triggers the oscilloscope and the arrival of the pulse in the receiver is recorded.

## 5.6 RESULTS

Pop plot and Hugoniot data were determined for three emulsion explosives (Emulsion A, Emulsion B, Emulsion C) and one solid explosive (finely ground ANFO) and three slurry explosives (Slurry A, Slurry B, and Slurry C). The emulsions are different in their aluminum content. Emulsion B contains 5% aluminum, Emulsion A contains 3% Al and Emulsion C does not contain any aluminum. More over Emulsion A and Emulsion B are #8 blasting cap sensitive whereas Emulsion C is a large diameter cap insensitive produce.

Slurry A and Slurry B are aluminized #8 blasting cap sensitive products and Slurry C is a non aluminized not cap sensitive slurry containing TNT prills.

In the following the Pop plots and the Hugoniot for each

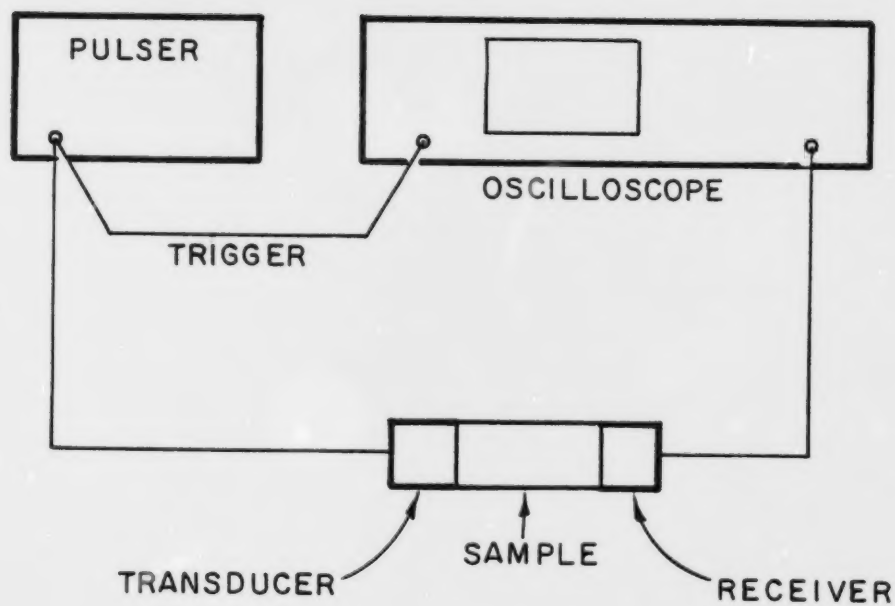


FIGURE 24: SET UP FOR THE SOUND VELOCITY MEASUREMENT.

particular explosive tested are presented.

a. ANFO

Prilled ammonium nitrate was ground to -200 mesh and mixed with fuel oil to form a composition of 94% by weight ammonium nitrate, 6% by weight fuel oil. The product was used to form wedges which were subjected to plane wave shocks of different amplitude by means of a plane wave generator booster and attenuator system.

The experimental results were analysed by using the reflected Hugoniot technique which was presented in Chapter 3.

Table 5.1 gives the measured data obtained from the wedge tests in the case of ANFO (-200 mesh, density = 0.95 g/cc).

Figure 25 presents the reflected Hugoniot technique in order to obtain the particle velocity in the explosive for the different measured shock velocities. To calculate the Hugoniot of the explosive the  $U_s$ ,  $U_p$  points from Figure 25 and the measured sound speed were considered. The measured sound speed was between 975 and 900 m/sec.

Thus the Hugoniot of ANFO can be expressed as:

$$U_s = 930 + 1.7 U_p \quad (5.6)$$

where  $U_s$ ,  $U_p$  are expressed in m/s.

The Hugoniot of the explosive is shown in Figure 25.

From Figure 25 and the relationship:

$$P = \rho_o U_s U_p$$



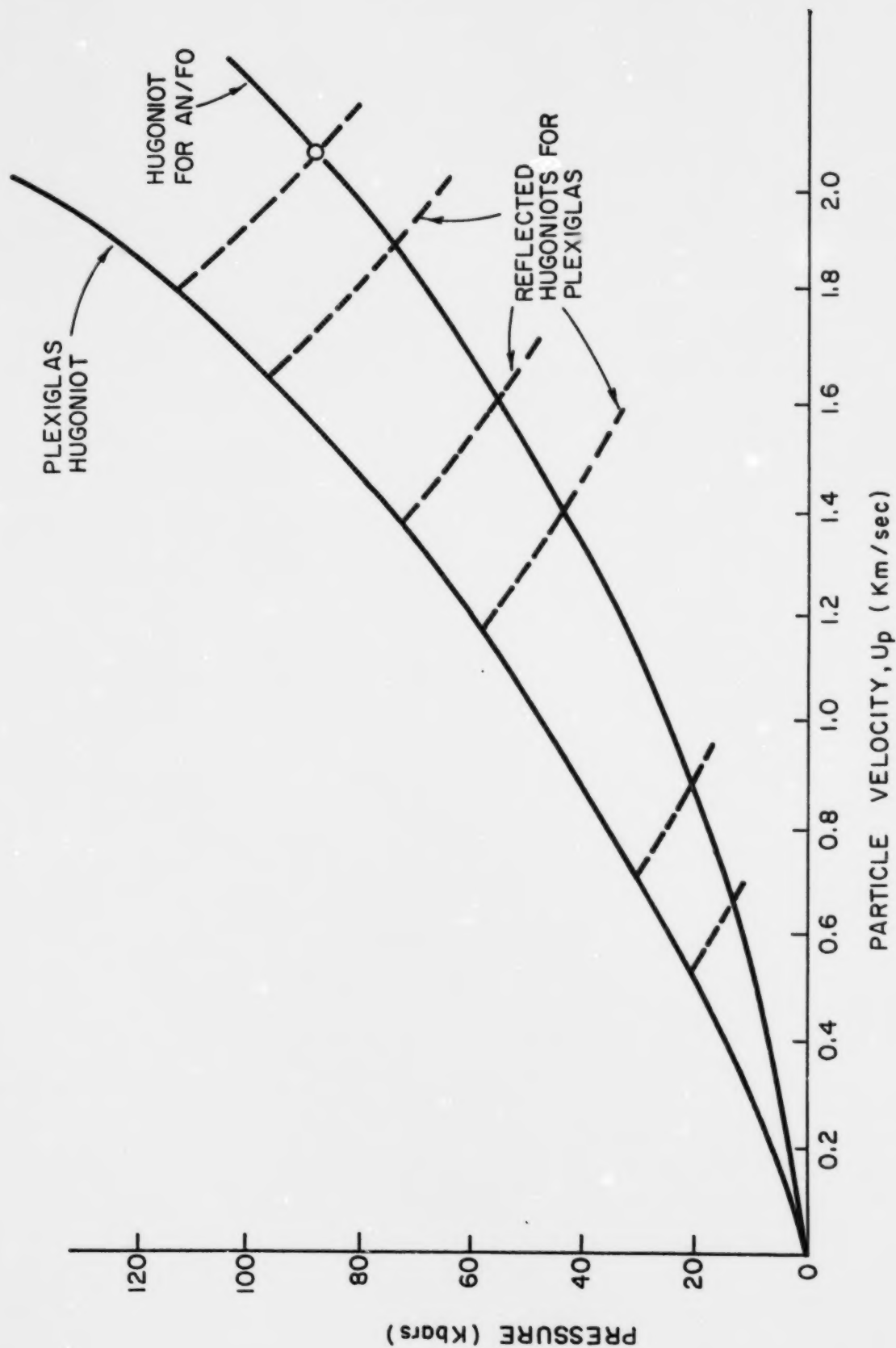


FIGURE 25: REFLECTED HUGONIOT TECHNIQUE FOR THE CALCULATION OF THE HUGONIOT FOR AN/FO ( $\rho = 0.95$  g/cc  
-200 MESH)

TABLE 5.1:     WEDGE TEST RESULTS FOR ANFO  
                  ( $\rho = 0.95 \text{ g/cc}$     -200 Mesh)

| Plexiglas<br>Thickness<br>(cm) | Initial Shock<br>Velocity<br>(m/s) | Distance of<br>Run to Detonation<br>(mm) |
|--------------------------------|------------------------------------|------------------------------------------|
| 1.27                           | 4500                               | 0.0                                      |
| 1.91                           | 4200                               | 2.0                                      |
| 3.81                           | 3640                               | 3.0                                      |
| 5.10                           | 3300                               | 4.0                                      |
| 10.16                          | 2600                               | 11.0                                     |
| 12.70                          | 2100                               | 21.0                                     |

where  $\rho_0$  is the initial density of the explosive  
 $U_s$  is the shock velocity and  
 $U_p$  is the particle velocity

the initial pressure in the wedge is calculated. Table 5.2 gives the relationship between initial pressure and distance of run to detonation for ANFO ( $\rho = 0.95$  g/cc - 200 mesh).

A linear fit of the logarithm of the distance of run (in cm) and the logarithm of the initial pressure (in Mbars) provides the following relationship (Pop plot):

$$\ln X^* = -4.74 - 1.24 \ln P \quad (5.7)$$

where  $X^*$  is the distance of run (cm) and  
 $P$  is the initial pressure (Mbars)

This relationship is presented in Figure 26.

#### b. Emulsion A

Emulsion A is an emulsion explosive which is #8 blasting cap sensitive. Its density is 1.15 g/cc and it is intended for small diameter blasting applications. Wedges of this product were made and subjected to plane shocks. The results of the wedge tests are shown in Table 5.3. These results were analysed by the reflected Hugoniot technique (Figure 27). From the data of Figure 27 and the sound speed of the explosive which was measured to be 1020 m/s the Hugoniot of the explosive can be expressed by:

$$U_s = 1092 + 1.76 U_p \quad (5.8)$$

where  $U_s$  is the shock velocity (m/s) and  
 $U_p$  is the particle velocity (m/s).

TABLE 5.2:    INITIAL PRESSURE VS DISTANCE OF RUN  
TO DETONATION FOR ANFO

| Plexiglas<br>Thickness | P<br>(Mbar) | lnP     | x*<br>(cm) | lnx*   |
|------------------------|-------------|---------|------------|--------|
| 1.27                   | 0.09        | -2.4079 | 0.0        | ----   |
| 1.91                   | 0.075       | -2.5903 | 0.2        | -1.514 |
| 3.81                   | 0.056       | -2.8824 | 0.3        | -1.273 |
| 5.10                   | 0.044       | -3.1236 | 0.4        | -0.755 |
| 10.16                  | 0.021       | -3.8632 | 1.1        | 0.0953 |
| 12.70                  | 0.017       | -4.0745 | 2.1        | 0.742  |

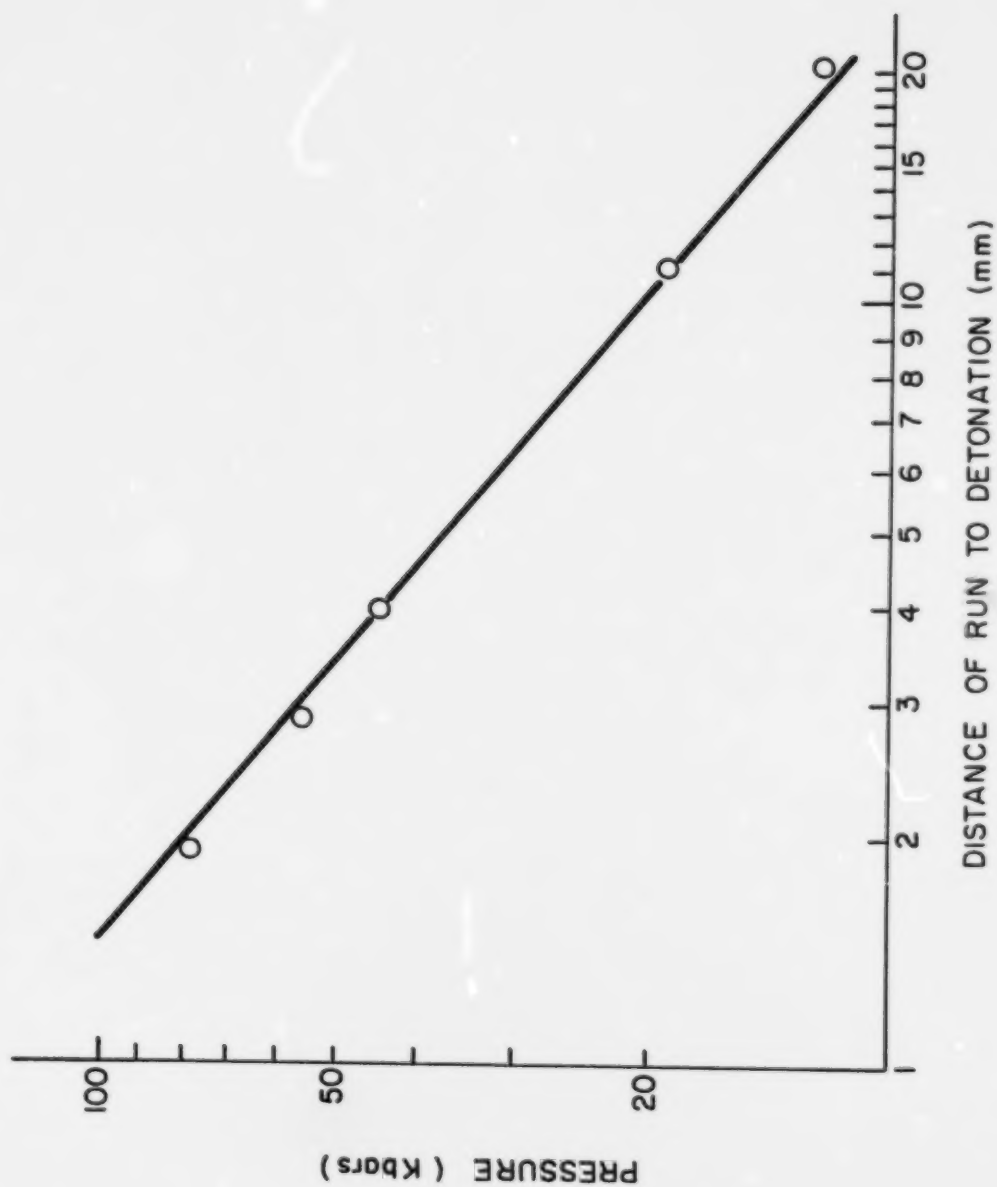


FIGURE 26: POP PLOT FOR AN/FO ( $\rho = 0.95$  g/cc -200 MESH)

TABLE 5.3:      WEDGE TEST RESULTS FOR EMULSION A

| Plexiglas<br>Thickness<br>(cm) | Distance of Run<br>to Detonation<br>(mm) | Initial Shock<br>Velocity<br>(m/s) |
|--------------------------------|------------------------------------------|------------------------------------|
| 1.27                           | 1.0                                      | --                                 |
| 1.90                           | 3.0                                      | 3900                               |
| 2.54                           | 4.0                                      | 4250                               |
| 3.18                           | 4.5                                      | 3500                               |
| 3.81                           | 5.0                                      | 4000                               |
| 5.08                           | 6.0                                      | 3600                               |
| 7.62                           | 6.0                                      | 3100                               |
| 8.90                           | 7.0                                      | --                                 |
| 10.16                          | -                                        | --                                 |
| 12.70                          | 1.80                                     | --                                 |

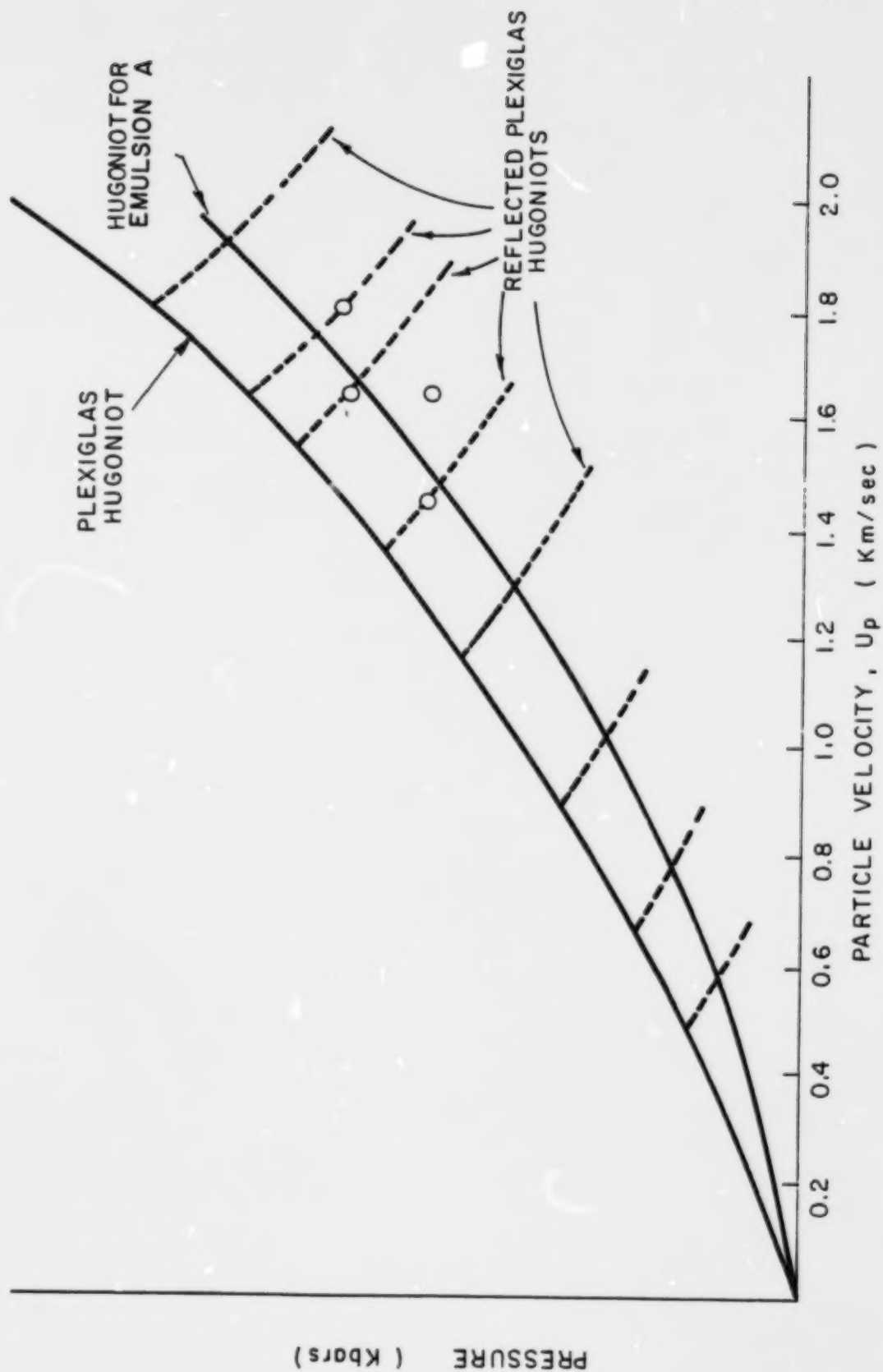


FIGURE 27: REFLECTED HUGONIOT TECHNIQUE FOR THE CALCULATION OF HUGONIOT FOR EMULSION A.



Table 5.4 gives the relationship between initial pressure and distance of run to detonation for Emulsion A. A linear fit of the logarithm of the distance of run (in cm) and the logarithm of the initial pressure in (Mbars) provides the following relationship (Pop plot).

$$\ln X^* = -3.85 - 1.03 \ln P \quad (5.9)$$

The Pop plot is shown in Figure 28.

c. Emulsion B

Emulsion B is a #8 blasting cap sensitive emulsion type explosive containing 5% aluminum flakes. Its density is 1.15 g/cc and it is used in small diameter commercial blasting applications. Wedges of this explosive were subjected to planar shocks. The results of the wedge tests are shown in Table 5.5. The results were analysed by the reflected Hugoniot technique (Figure 29). From the data of Figure 29 and the sound speed of the explosive which was measured to be 1030 m/s the Hugoniot of the explosive can be expressed as:

$$U_s = 1300 + 1.6 U_p \quad (5.10)$$

where  $U_s$  is the shock velocity (m/s) and  
 $U_p$  is the particle velocity (m/s)

Table 5.6 presents the relationship between initial pressure and distance of run to detonation for Emulsion B. A linear fit of the logarithm of the distance of run (in cm) and the logarithm of the logarithm of the initial pressure in Mbars provides the following relationship (Pop plot).

$$\ln X^* = -3.7 - 1.04 \ln P \quad (5.11)$$

TABLE 5.4: INITIAL PRESSURE VS DISTANCE OF RUN TO EMULSION A

| Initial Pressure (Mbars) | lnP    | Distance of Run to Detonation (cm) | lnx*   |
|--------------------------|--------|------------------------------------|--------|
| 0.102                    | -2.283 | 0.0                                | --     |
| 0.086                    | -2.453 | 0.3                                | -1.204 |
| 0.079                    | -2.538 | 0.4                                | -0.916 |
| 0.071                    | -2.645 | 0.45                               | -0.798 |
| 0.065                    | -2.733 | 0.4                                | -0.916 |
| 0.050                    | -2.946 | 0.6                                | -0.511 |
| 0.034                    | -3.382 | 0.6                                | -0.511 |
| 0.025                    | -3.689 | 0.7                                | -0.357 |
| 0.014                    | -4.268 | 1.8                                | 0.588  |

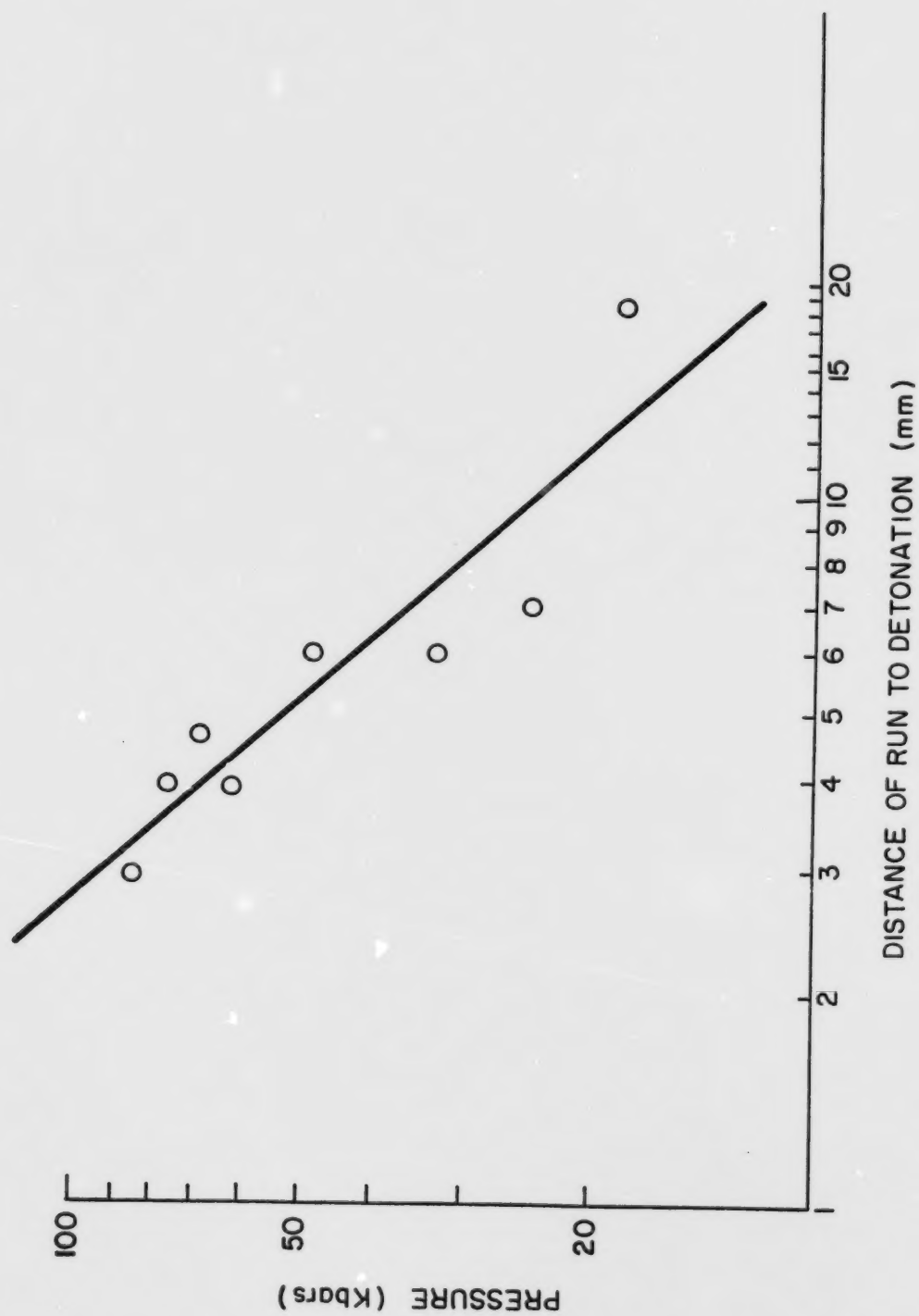


FIGURE 28 : POP PLOT FOR EMULSION A

TABLE 5.5:      WEDGE TEST RESULTS FOR EMULSION B

| Plexiglas<br>Thickness<br>(cm) | Distance of Run<br>to Detonation<br>(mm) | Initial Shock<br>Velocity<br>(m/sec) |
|--------------------------------|------------------------------------------|--------------------------------------|
| 1.27                           | 2.0                                      | 3700                                 |
| 1.9                            | 3.0                                      | 4200                                 |
| 2.54                           | 8.0                                      | 4300                                 |
| 3.81                           | 5.0                                      | 3600                                 |
| 4.44                           | 6.0                                      | --                                   |
| 5.04                           | 7.0                                      | 3700                                 |
| 10.16                          | 10.0                                     | 3500                                 |

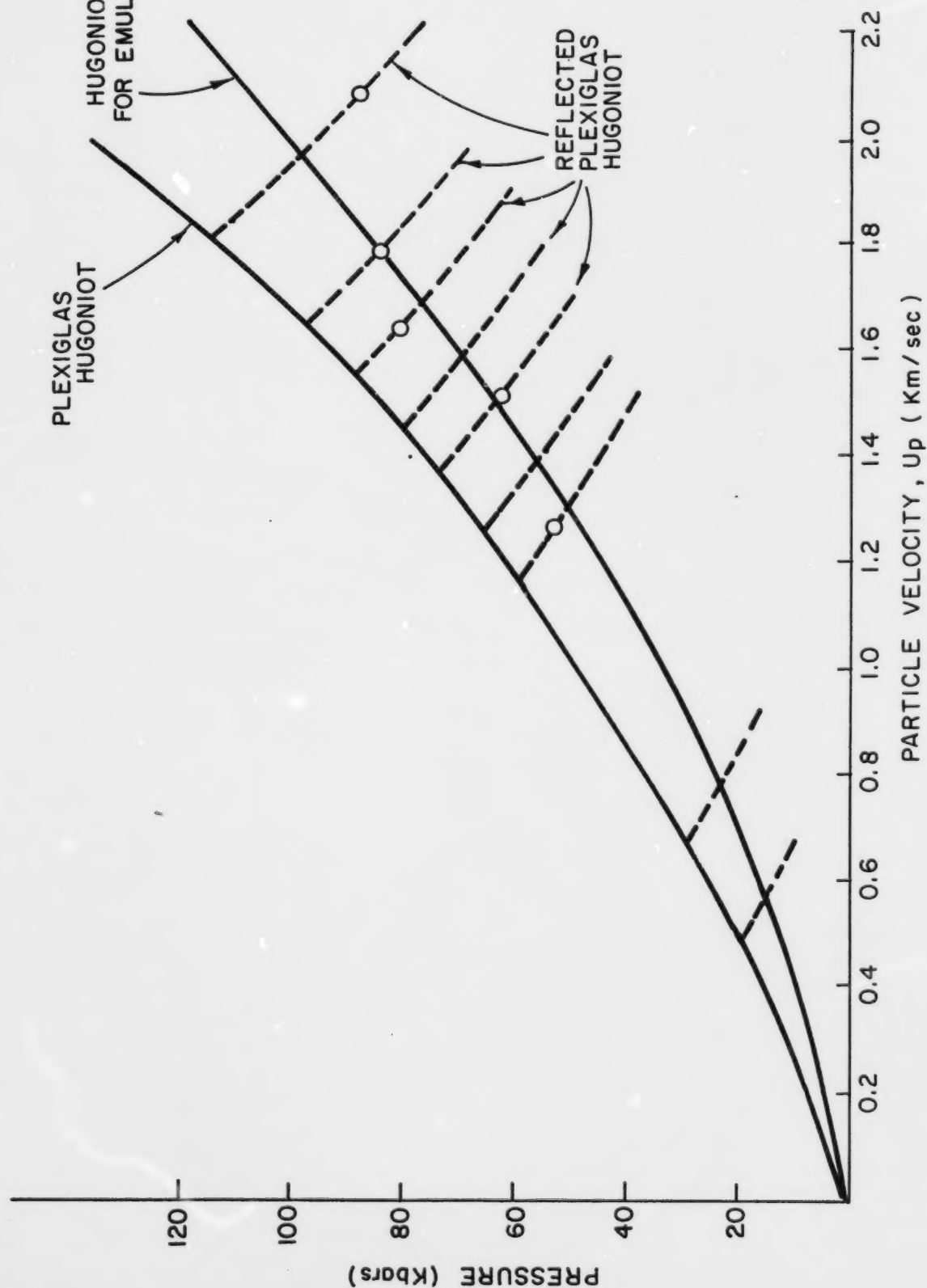


FIGURE 29 : REFLECTED HUGONIOT TECHNIQUE FOR THE CALCULATION OF THE HUGONIOT FOR EMULSION B

**TABLE 5.6: INITIAL PRESSURE VS DISTANCE OF RUN FOR EMULSION B**

| Initial Pressure P<br>(Mbars) | lnP      | Distance of Run<br>to Detonation x* | lnx*    |
|-------------------------------|----------|-------------------------------------|---------|
| 0.100                         | -2.3026  | 0.2                                 | -1.6094 |
| 0.085                         | -2.4651  | 0.3                                 | -1.2050 |
| 0.077*                        | -2.5639  | 0.8                                 | -0.2231 |
| 0.064                         | -2.7489  | 0.5                                 | -0.6931 |
| 0.057                         | -2.8647  | 0.6                                 | -0.5108 |
| 0.052                         | -2.9565  | 0.7                                 | -0.3567 |
| 0.023                         | -3.77226 | 1.0                                 | 0.0     |

\* Rejected

The Pop plot is shown in Figure 30.

d. Emulsion C

Emulsion C is a large diameter non cap sensitive emulsion explosive. Its density is 1.25 g/cc. Wedge tests were conducted in the same manner as for the previous explosives. The results of the wedge tests are shown in Table 5.7. The results again are analysed by the reflected Hugoniot technique (Figure 31). The unreacted Hugoniot of the product can be expressed by the relationship:

$$U_s = 1300 + 1.6 U_p \quad (5.12)$$

where  $U_s$  and  $U_p$  are in m/s.

Table 5.8 presents the relationship between initial pressure and distance of run to detonation for Emulsion C. A linear fit of the logarithm of the distance of run (in cm) and the logarithm of the initial pressure in Mbars provides the following relationship (pop plot).

$$\ln X^* = -6.22 - 2.25 \ln P \quad (5.13)$$

The pop plot is shown in Figure 32.

e. Slurry A

Slurry A is an aluminized slurry explosive. It is #8 blasting cap sensitive and its density is 1.25 g/cc. The results of the wedge tests conducted to determine its pop plot and Hugoniot relationships are shown in Table 5.9. The results are analysed by the reflected Hugoniot technique in Figure 33.



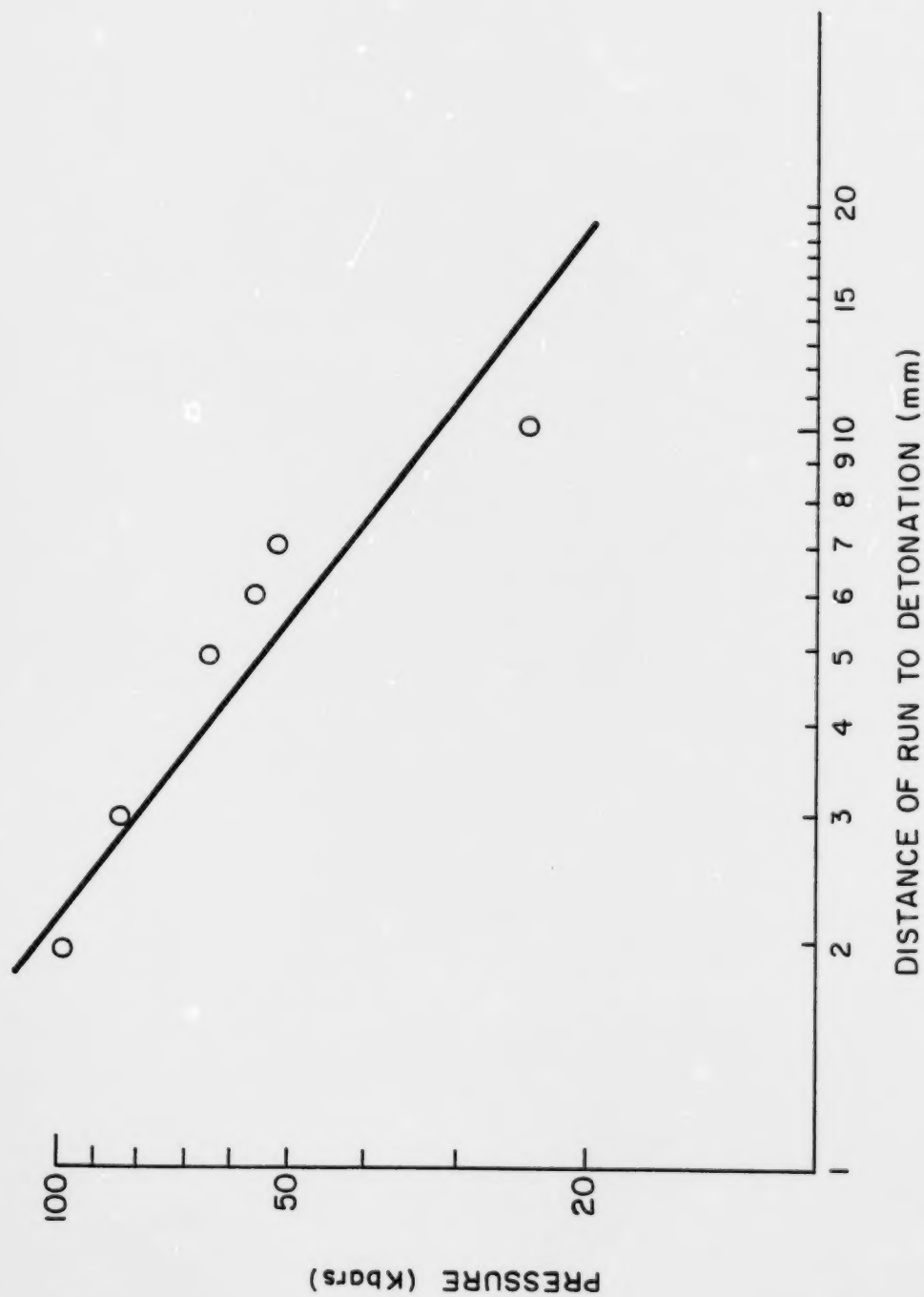


FIGURE 30 : POP PLOT FOR EMULSION B

TABLE 5.7:    WEDGE TEST RESULTS FOR EMULSION C

| Plexiglas<br>Thickness<br>(cm) | Distance of Run<br>to Detonation<br>(mm) | Initial Shock<br>Velocity<br>(m/s) |
|--------------------------------|------------------------------------------|------------------------------------|
| 1.3                            | 0.3                                      | 3800                               |
| 1.9                            | 0.7                                      | 4500                               |
| 2.5                            | 0.6                                      | --                                 |
| 3.1                            | 0.8                                      | 3900                               |

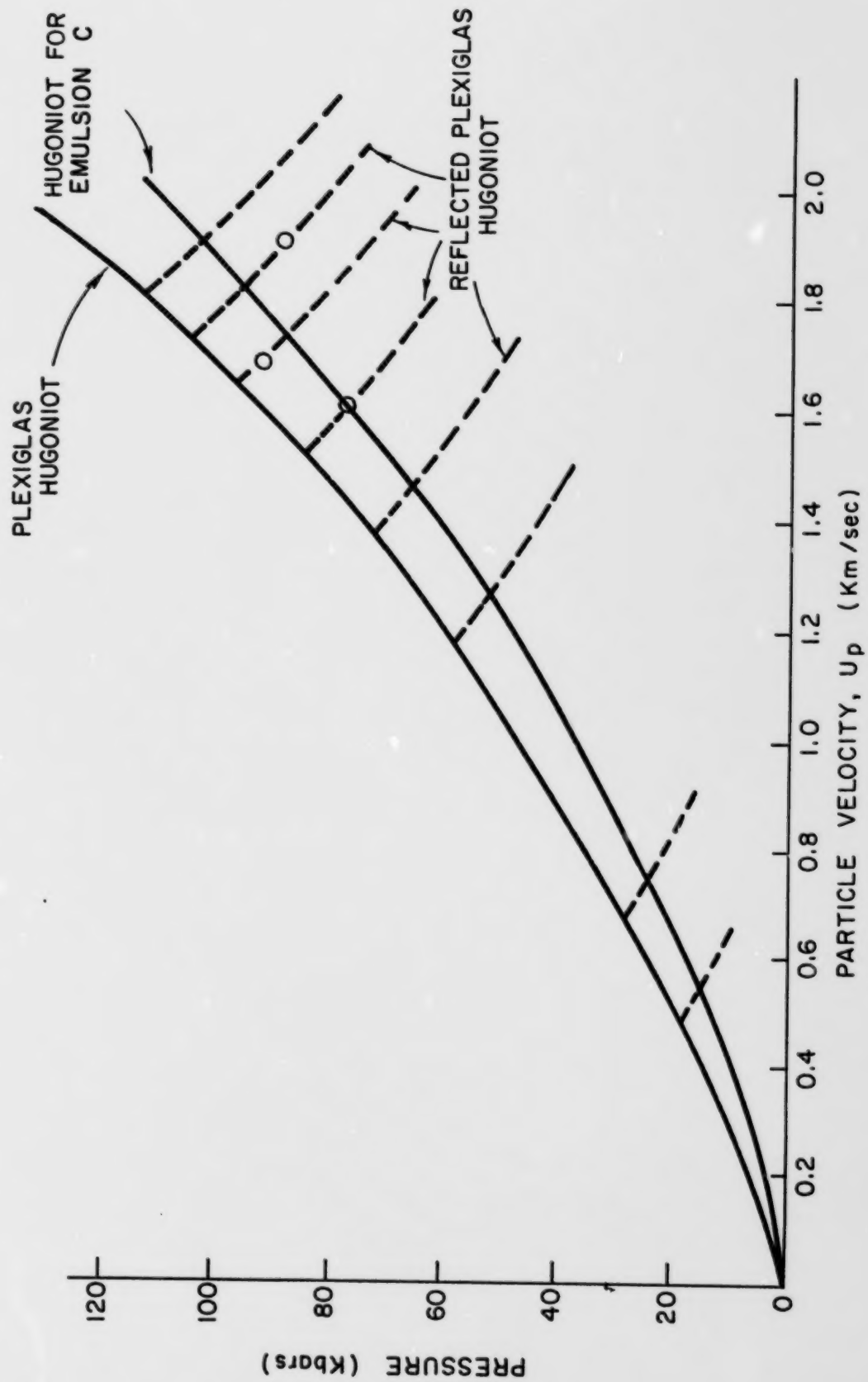


FIGURE 31: REFLECTED HUGONIOT TECHNIQUE FOR THE CALCULATION OF THE HUGONIOT FOR EMULSION C

**TABLE 5.8:    INITIAL PRESSURE VS DISTANCE OF RUN TO DETONATION**  
**FOR EMULSION C**

| Initial<br>Pressure<br>(Mbars) | $\ln P$ | Distance of Run<br>to Detonation<br>(cm) | $\ln x^*$ |
|--------------------------------|---------|------------------------------------------|-----------|
| 0.100                          | -2.3025 | 0.3                                      | -1.2039   |
| 0.085                          | -2.4651 | 0.7                                      | -0.3567   |
| 0.077                          | -2.5639 | 0.6                                      | -0.5108   |
| 0.070                          | -2.6593 | 0.8                                      | -0.2231   |
| 0.064                          | -2.7488 | 0.9                                      | -0.1054   |

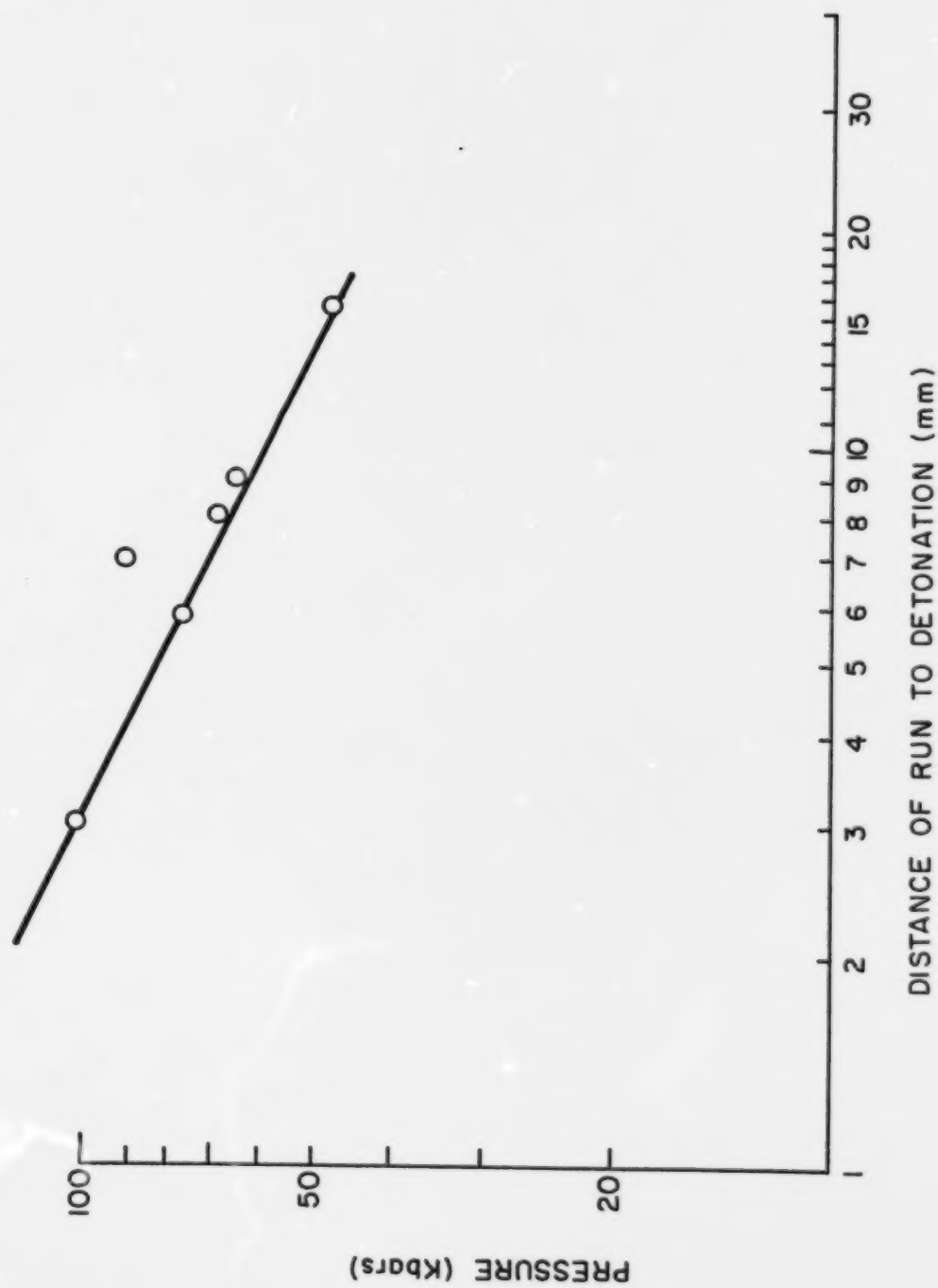


FIGURE 32: POP PLOT FOR EMULSION C

TABLE 5.9: WEDGE TEST RESULTS FOR SLURRY A

| Plexiglas Thickness (cm) | Distance of Run to Detonation (cm) | Initial Shock Velocity (m/s) |
|--------------------------|------------------------------------|------------------------------|
| 1.3                      | --                                 | --                           |
| 2.5                      | 0.2                                | 3500                         |
| 5.1                      | 0.5                                | 3240                         |
| 7.6                      | 0.6                                | 3140                         |
| 10.2                     | 0.7                                | 2850                         |
| 12.7                     | 1.0                                | 2870                         |
| 13.3                     | 1.9                                | -*                           |
| 14.6                     | 1.4                                | -*                           |

\*TRACE NOT CLEAR close to the interface between plexiglas wafer and explosive wedge

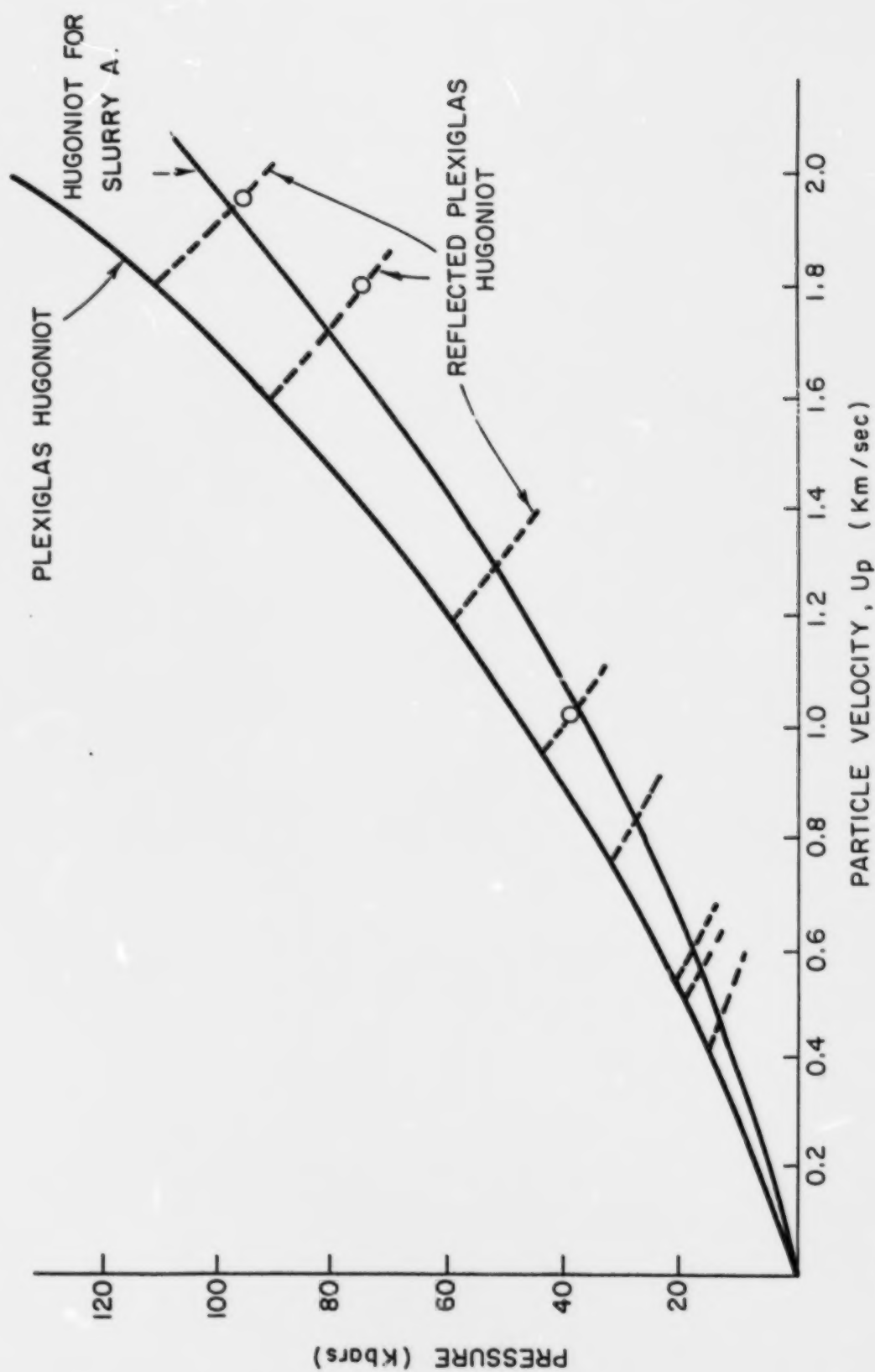


FIGURE 33 . REFLECTED HUGONIOT TECHNIQUE FOR THE CALCULATION OF THE HUGONIOT FOR SLURRY A



The unreacted Hugoniot of the explosive can be expressed as:

$$U_s = 1700 + 1.22 U_p \quad (5.14)$$

where  $U_s, U_p$  are in m/sec.

The relationship between initial pressure and distance of run to detonation is shown in Table 5.10 and Figure 34. The Pop plot can be expressed as:

$$\ln X^* = -3.1 - 0.85 \ln P \quad (5.15)$$

#### f. Slurry B

Slurry B is a #8 cap sensitive aluminized slurry explosive having an initial density of 1.25 g/cc. The results of the wedge tests conducted to determine its Pop plot and Hugoniot relationships are shown in Table 5.11. The results are analysed by the reflected Hugoniot technique in Figure 35. The unreacted Hugoniot of the explosive can be expressed as:

$$U_s = 1500 + 1.72 U_p \quad (5.16)$$

where  $U_s, U_p$  are in m/s.

The relationship between the initial pressure impacting the explosive and the distance of run to detonation is shown in Table 5.12 and Figure 36. The Pop plot can be expressed as:

$$\ln X^* = -4.13 - 1.09 \ln P \quad (5.17)$$

where  $X^*$  is in cm and  $P$  in Mbars.

TABLE 5.10:     INITIAL PRESSURE VS DISTANCE OF RUN TO  
DETONATION FOR SLURRY B

| Initial Pressure<br>(Mbars) | lnP    | Distance of Run<br>to Detonation<br>(cm) | lnx    |
|-----------------------------|--------|------------------------------------------|--------|
| 0.099                       | -2.313 | 0.0                                      | --     |
| 0.082                       | -2.489 | 0.2                                      | -1.609 |
| 0.058                       | -2.847 | 0.5                                      | -0.693 |
| 0.041                       | -3.194 | 0.6                                      | -0.511 |
| 0.029                       | -3.541 | 0.7                                      | -0.357 |
| 0.019                       | -3.963 | 1.0                                      | 0.0    |
| 0.017                       | -4.074 | 1.9                                      | 0.642  |
| 0.014                       | -4.269 | 1.4                                      | 0.336  |

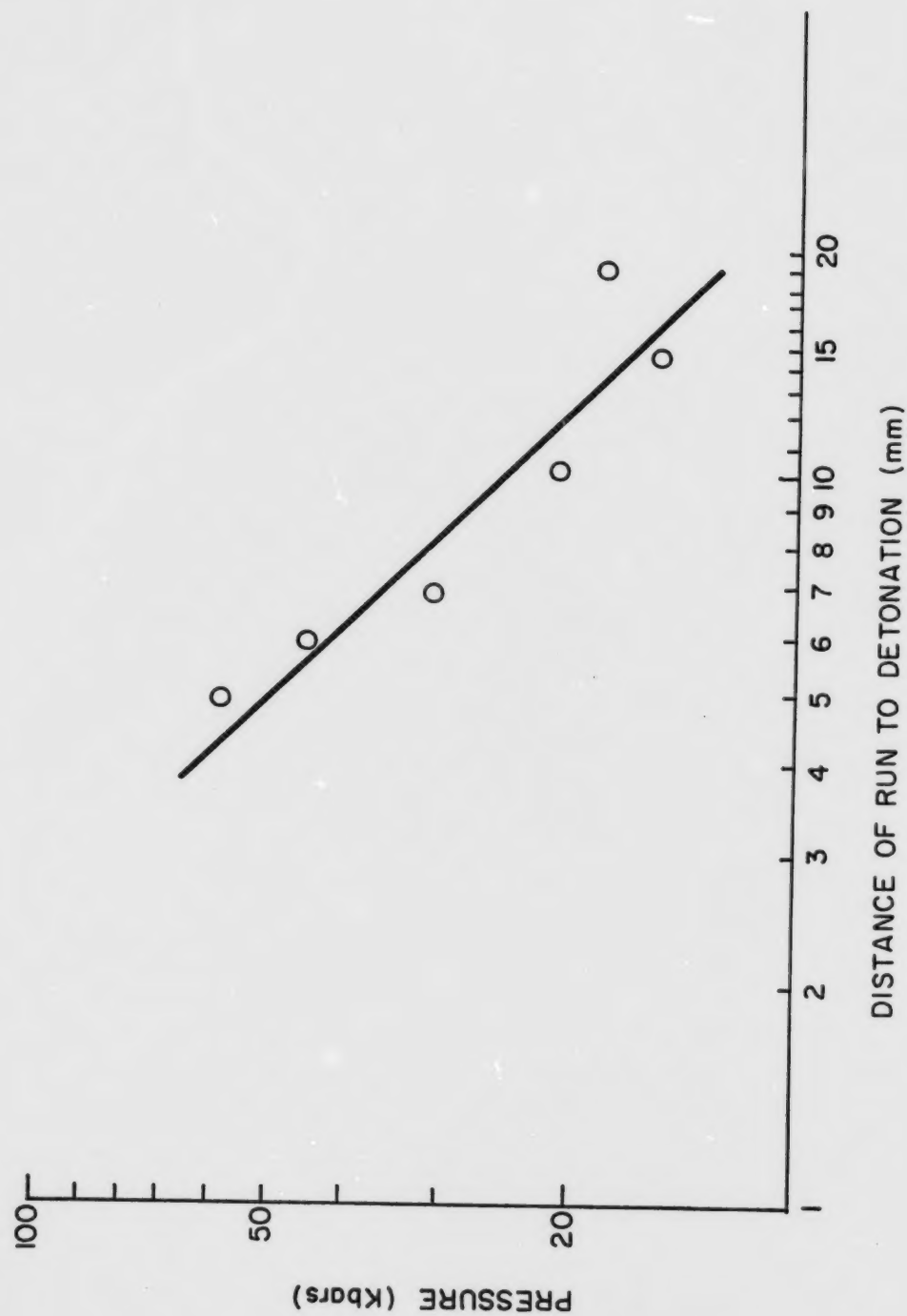


FIGURE 34: POP PLOT FOR SLURRY A

TABLE 5.11: WEDGE TEST RESULTS FOR SLURRY B

| Plexiglas Thickness<br>(cm) | Distance of Run<br>to Detonation<br>(cm) | Initial Shock<br>Velocity<br>(m/s) |
|-----------------------------|------------------------------------------|------------------------------------|
| 6.3                         | 0.1                                      | 3600                               |
| 7.0                         | 0.4                                      | 3200                               |
| 7.6                         | 0.6                                      | 3600                               |
| 9.5                         | -                                        | -- decelerates                     |
| 12.7                        | 1.2                                      | 2400                               |

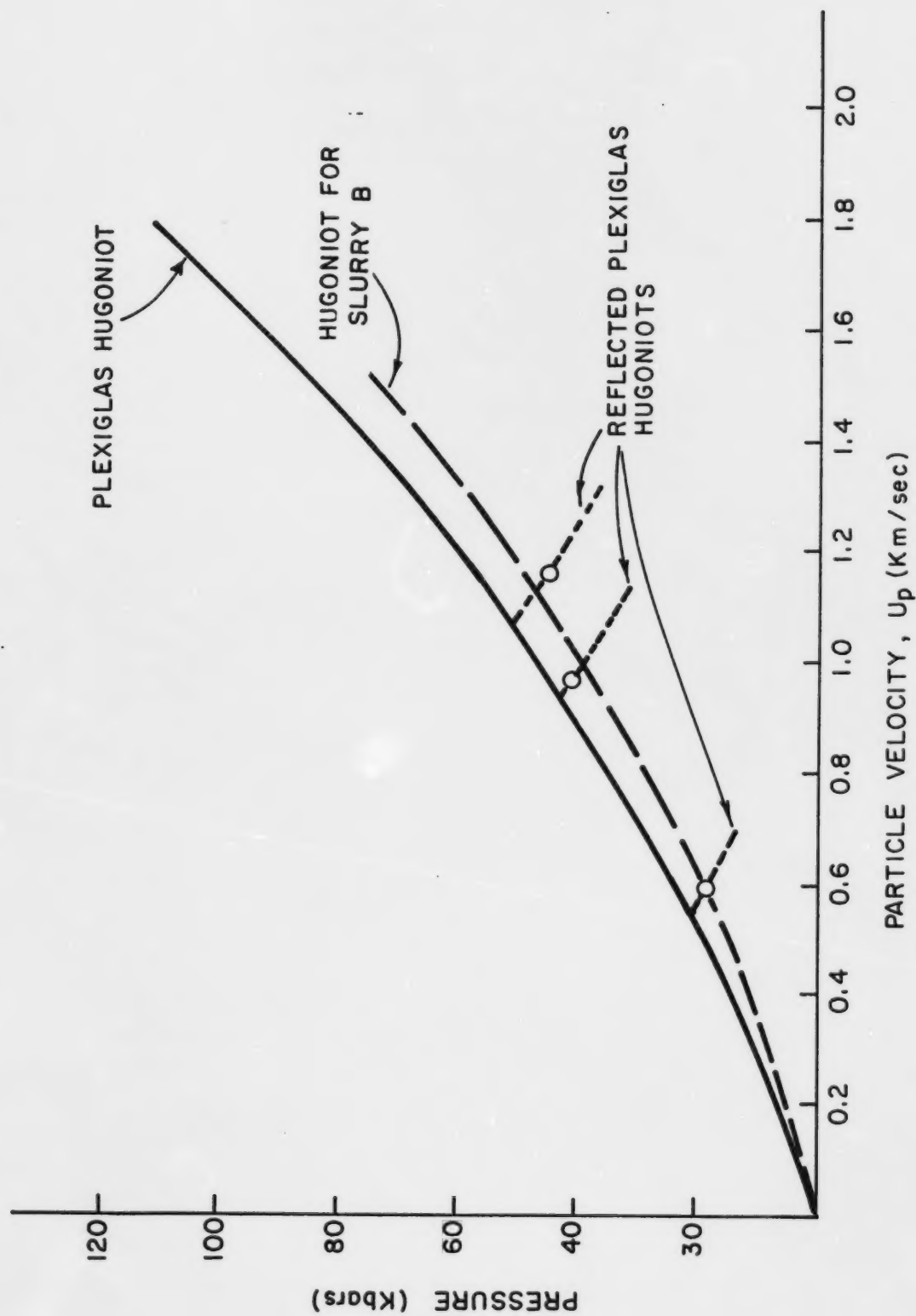


FIGURE 35: REFLECTED HUGONIOT TECHNIQUE FOR THE CALCULATION OF THE HUGONIOT FOR SLURRY B

TABLE 5.12: INITIAL PRESSURE VS DISTANCE OF RUN  
TO DETONATION FOR SLURRY B

| Initial<br>Pressure<br>(Mbars) | $\ln P$ | Distance of Run<br>to Detonation<br>(cm) | $\ln x^*$ |
|--------------------------------|---------|------------------------------------------|-----------|
| 0.052                          | -3.08   | 0.9                                      | -0.105*   |
| 0.049                          | -3.02   | 0.4                                      | -0.916    |
| 0.040                          | -3.22   | 0.6                                      | -0.511    |
| 0.019                          | -3.96   | 1.2                                      | 0.182     |

\* Out of sequence - rejected

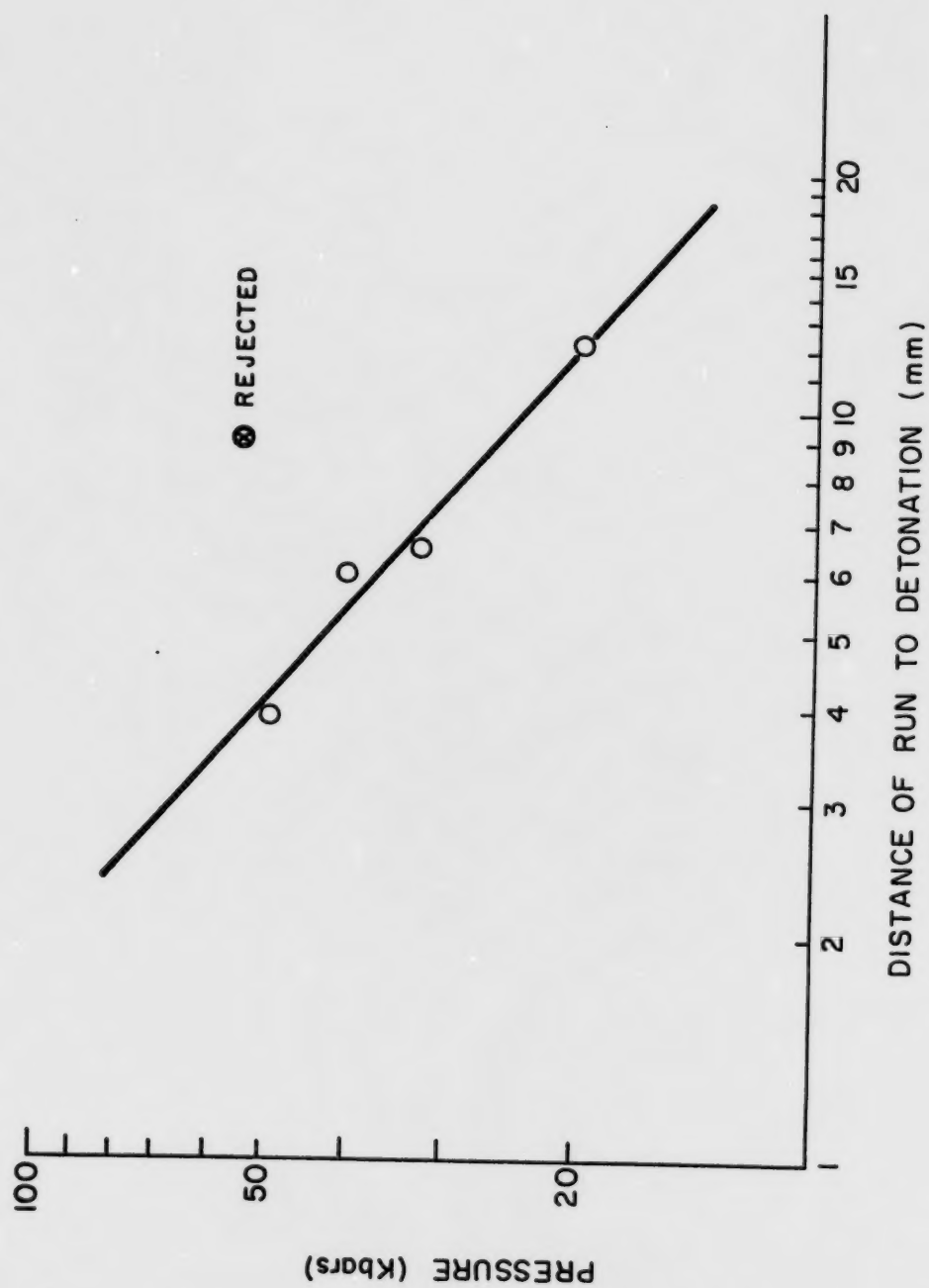


FIGURE 36: POP PLOT FOR SLURRY B

g. Slurry C

Slurry C is a slurry explosive containing TNT prills. It is not cap insensitive and it is used in large diameter commercial blasting applications. Table 5.13 gives the measured data from the wedge tests conducted for the case of Slurry C. It is observed that although a large number of experiments were conducted the corresponding number of useful results is very limited. This is due to the fact that the large number of TNT prills make the explosive very inhomogeneous. Essentially a new composition is examined in each wedge test because of the variation in the TNT location or distribution.

Due to the inconsistency of the results and the wide scatter which was observed no attempt was made to further analyse the results for the case of Slurry C. It must be noted here that similar difficulties have been encountered by researchers in the field of coarse granular explosives. Figure 37 shows the Pop plot determined for coarse Nitroguanidine by the Los Alamos Scientific Laboratory Group (10).



TABLE 5:13:    WEDGE TEST RESULTS FOR SLURRY C

| Plexiglas<br>Thickness<br>(cm) | Distance of Run<br>to Detonation<br>(mm) | Initial Shock<br>Velocity |
|--------------------------------|------------------------------------------|---------------------------|
| 1.27                           | 2.0                                      | --                        |
| 1.905                          | 4.0                                      | 4069                      |
| 2.54                           | 0.0                                      | --                        |
| 3.81                           | 8.0                                      | 4558                      |
| 5.08                           | 3.0                                      | decelerates               |
| 10.16                          | 41.0                                     | 3328                      |
| 12.7                           | decelerates                              |                           |
| 15.24                          | failed                                   |                           |

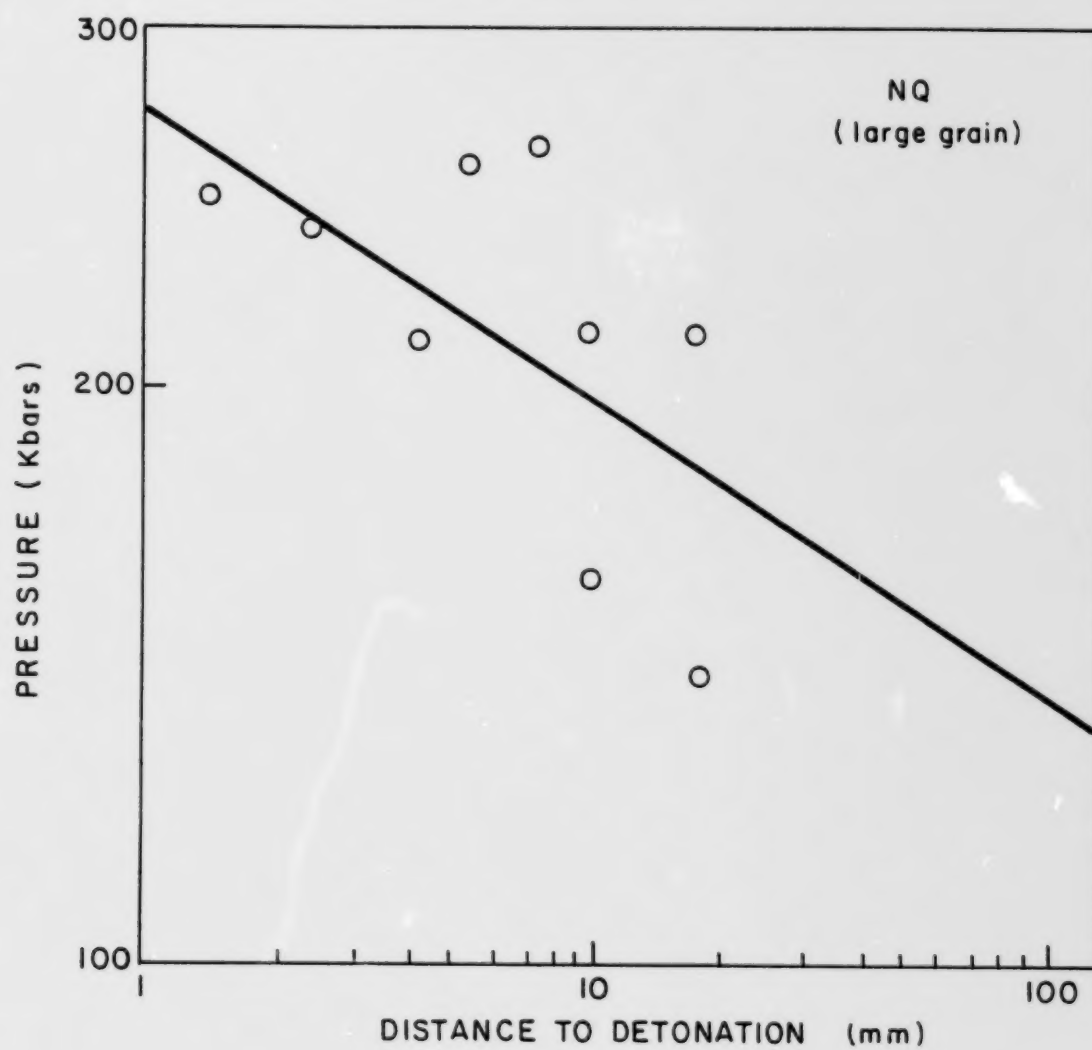


FIGURE 37: POP PLOT FOR NITROQUANIDINE

## CHAPTER SIX

### CALCULATED DATA FOR THE MODEL

#### 6.0 INTRODUCTION

For the modelling of the impact initiation the following data must be provided:

- a. The HOM equation of state parameters
- b. The Forest Fire rate coefficients.

These data are presented in the present chapter.

#### 6.1 HOM EQUATION OF STATE PARAMETERS

HOM calculates the pressure and temperature, given the internal energy, specific volume and the mass fraction of the reacted material in the case of an explosive. Obviously in the case of a non reactive material the fraction is equal to 0 for solids and 1 for gases. The HOM equation of state was presented in Chapter 3. The parameters for the explosives under study are given in Tables 6.1 and 6.2. In the tables the same nomenclature with Chapter 3 has been kept.

The parameters for the gaseous products were calculated by computing as isentrope through the C-J point by using the TIGER thermohydrodynamic code.

#### 6.2 FOREST FIRE COEFFICIENTS

Forest Fire has been developed for calculating reaction

TABLE 6.1: HOM EQUATION OF STATE PARAMETERS FOR UNREACTED EXPLOSIVES

| Parameter      | ANFO    | Emulsion A | Emulsion B | Emulsion C | Slurry A | Slurry B |
|----------------|---------|------------|------------|------------|----------|----------|
| C              | 0.9300  | 1.0920     | 1.3000     | 1.300      | 1.7000   | 1.4700   |
| S              | 1.7000  | 1.7000     | 1.6000     | 1.6000     | 1.2200   | 1.8400   |
| P              | 5.8000  | 5.4100     | 5.4600     | 4.9000     | 4.5506   | 4.9910   |
| G              | -1.1000 | -3.2500    | -2.1082    | -7.2000    | -1.0165  | -5.4810  |
| H              | 1.4000  | -1.1200    | -3.8107    | -2.4000    | -3.1876  | -1.1350  |
| I              | 7.1000  | -1.8190    | -4.3604    | -3.3000    | -4.1606  | -1.2930  |
| J              | 1.4000  | -5.2500    | 2.4251     | -1.2580    | -1.3220  | 2.1880   |
| V              | 1.0526  | 0.8700     | 0.8700     | 0.8000     | 0.8000   | 0.8000   |
| C <sub>v</sub> | 0.5000  | 0.8700     | 0.3000     | 0.5000     | 0.5000   | 0.5000   |
| Y              | 1.5000  | 1.5000     | 1.500      | 1.5000     | 1.5000   | 0.5000   |

TABLE 6.2: NOM EQUATION OF STATE PARAMETERS FOR REACTION PRODUCTS

| Parameter      | ANFO        | Emulsion<br>A | Emulsion<br>B | Emulsion<br>C | Slurry<br>A | Slurry<br>B |
|----------------|-------------|---------------|---------------|---------------|-------------|-------------|
| A              | -3.2274 00  | -3.5611 00    | -3.5574 00    | -3.6187 00    | -3.6448 00  | -3.5480 00  |
| B              | -2.3817 00  | -2.6123 00    | -2.5322 00    | -2.8222 00    | -2.6307 00  | -2.5779 00  |
| C              | 1.8280 -01  | 3.5412 -01    | 3.7529 -01    | 3.0057 -01    | 3.8424 -01  | 3.6590 -01  |
| D              | -1.3714 -03 | -4.5411 -02   | -5.7202 -02   | -2.3017 -02   | -5.9307 -02 | -5.6860 -02 |
| E              | 1.7234 -03  | 2.6874 -03    | 4.3719 -03    | 3.5313 -03    | 5.0914 -03  | 6.3297 -03  |
| K              | -1.3400 00  | -1.4967 00    | -1.5054 00    | -1.5027 00    | -1.5488 00  | -1.5120 00  |
| L              | 4.7079 -01  | 4.3413 -01    | 4.2150 -01    | 4.6443 -01    | 4.1976 -01  | 4.3848 -01  |
| M              | 6.6484 -02  | 6.9297 -02    | 6.5291 -02    | 7.8915 -02    | 6.5663 -02  | 6.8011 -02  |
| N              | 4.6626 -03  | 5.5666 -03    | 5.1942 -03    | 6.5088 -03    | 5.1123 -03  | 5.3612 -03  |
| O              | 1.3022 -04  | 1.8017 -04    | 1.6703 -04    | 2.1306 -04    | 1.5845 -04  | 1.7095 -04  |
| Q              | 7.5601 00   | 7.2737 00     | 7.4376 00     | 6.8707 -01    | 7.2217 00   | 7.3391 00   |
| R              | -5.1034 -01 | -4.2798 -01   | -3.7176 -01   | -5.8901 -01   | -4.2116 -01 | -4.0064 -01 |
| S              | 5.2928 -02  | 3.0917 -02    | 3.9422 -02    | -1.1041 -02   | 3.4204 -02  | 3.0518 -02  |
| T              | 1.1691 -03  | 1.2431 -02    | 2.9939 -03    | 5.3010 -02    | 7.8817 -03  | 1.9304 -02  |
| U              | -1.7044 -03 | -4.7497 -03   | -2.4892 -03   | -1.2437 -03   | -2.8768 -03 | -9.7117 -03 |
| C <sub>v</sub> | 0.5700 00   | 0.5700 00     | 0.5700 00     | 0.6000 00     | 0.5860 00   | 0.6180 00   |
| Z              | 0.1000 00   | 0.1000 00     | 0.1000 00     | 0.100 00      | 0.1000 00   | 0.1000 00   |

rates as a function of the Pop plots and the reactive and the non reactive Hugoniot of the explosive. The reaction rates were calculated by using the "FFIRE" code which was obtained from the Los Alamos Laboratories and adjusted to run on desk-top personal computers.

The Pop plots and the non reactive Hugoniot were determined experimentally and they were presented in Chapter 5. The reactive Hugoniot is determined by knowing the initial sound speed of the explosive and the shock velocity and particle velocity at the C-J point, which are calculated by using the TIGER code. The assumption is made here that the shock velocity and particle velocity are related linearly.

In order to use the calculated rates in the hydrodynamic model they must be fitted by a least square fit to the polynomial

$$\ln(\text{rate}) = \sum_{i=1}^n A_i P^{i-1} \quad (6.1)$$

where  $P$  is the pressure

and  $\text{rate} = -\frac{1}{W} \frac{dW}{dt}$  with  
 $W$  the fraction of unreacted explosive and  
 $t$  the time in sec

The coefficients of the fits of the rate and the pressure according to equation (6.1) are shown in Table 6.3.

TABLE 6.3: CALCULATED FOREST FIRE RATE COEFFICIENTS

| COEFFICIENT    | EXPLOSIVE        |                  |                  |                  |                   |                   |
|----------------|------------------|------------------|------------------|------------------|-------------------|-------------------|
|                | ANFO             | EMULSION<br>A    | EMULSION<br>B    | EMULSION<br>C    | SLURRY<br>A       | SLURRY<br>B       |
| A <sub>1</sub> | -.1075861659D+02 | -.9046066056D+01 | -.9113146314D+01 | -.1492840321D+02 | -.8718857716D+01  | -0.9255816483D 01 |
| A <sub>2</sub> | .1359146974D+04  | .1070838335D+04  | .1013327084D+04  | .1042229673D+04  | .9371610540D+03   | 0.8484155802D 03  |
| A <sub>3</sub> | -.1071191262D+06 | -.7807327734D+05 | -.7234762116D+05 | -.4964019796D+05 | -.6977051539D+05  | -0.4887403548D 05 |
| A <sub>4</sub> | .4956307810D+07  | .3342003255D+07  | .3105141708D+07  | .1477972021D+07  | .3267552455D+07   | 0.1740735134D 07  |
| A <sub>5</sub> | -.1301466689D+09 | -.8102645676D+08 | .7614127873D+08  | -.2583025999D+08 | -.89776271495D+08 | -0.3597003228D 08 |
| A <sub>6</sub> | .1925424189D+10  | .1105627111D+10  | .1056095301D+10  | .2593106274D+09  | .1415394762D+10   | 0.4237603824D 09  |
| A <sub>7</sub> | -.1494139566D+11 | .7907503561D+10  | -.7702494718D+10 | -.1381904214D+10 | -.1183773742D+11  | -0.2636905595D 10 |
| A <sub>8</sub> | .4731201670D+11  | .2306506085D+11  | .2295894653D+11  | .3028634971D+10  | .4066029414D+11   | 0.6720930346D 10  |

## CHAPTER SEVEN

### COMPARISON BETWEEN CALCULATED AND EXPERIMENTAL RESULTS FOR IMPACT SENSITIVITY OF EXPLOSIVES

#### 7.0 INTRODUCTION

In order to evaluate the reactive hydrodynamic model "HYDREL" the predictions of the code were compared against impact sensitivity data obtained experimentally. The evaluation covered the commercial explosives for which the equation of state parameters and the reaction rate laws were determined at an earlier stage of this study and one military explosive, data for which were obtained from the existing literature. Impact sensitivity experimental data for the commercial products were obtained at our test facility while impact sensitivity data for the military explosive were found in the literature.

#### 7.1 EXPERIMENTAL

The high velocity impact sensitivity of commercial explosives was determined by the following three types of experiments:

- a. Projectile impact tests
- b. High velocity small projectile tests (bullet tests)
- c. Flyer plate impact tests

In the following these experiments will be discussed.



a. Projectile Impact Test

In this type of test aluminum projectiles were fired from a cannon at an explosive target. A series of tests was conducted by varying projectile velocity and diameter. The projectile diameters were 2.5 cm, 5.1 cm, 10.2 cm and 15.2 cm. Usually the explosives were tested unconfined. However in some cases the explosives were confined in order to evaluate the effect of confinement. Confinement was achieved by placing the explosive in schedule 40 steel pipes. The projectile velocity was calculated by reading the time interval for passage of the projectile between two light sensors placed a known distance apart in front of the target.

The experimental set up is shown in Figure 38. The impact was observed by a HYCAM high speed framing camera having a writing speed of 3000 frames per second. Thus the detonation or failure can be determined by the review of the film. The result can also be characterized by the deformation of the projectile after impact. Figure 39 shows a projectile before and after impact in which a failure occurred. Figure 40 shows a projectile before and after impact when the result was a detonation. The deformation of the projectile is significant in this case.

Moreover the result can be characterized by the remains of the target explosive. In case of a detonation no remains of the target explosive are found.

The results of the cannon tests are presented in Table 7.1.

b. High Velocity Small Projectile Tests

For the case of the #8 cap sensitive emulsion explosives small projectiles were used. Small projectiles can travel fast

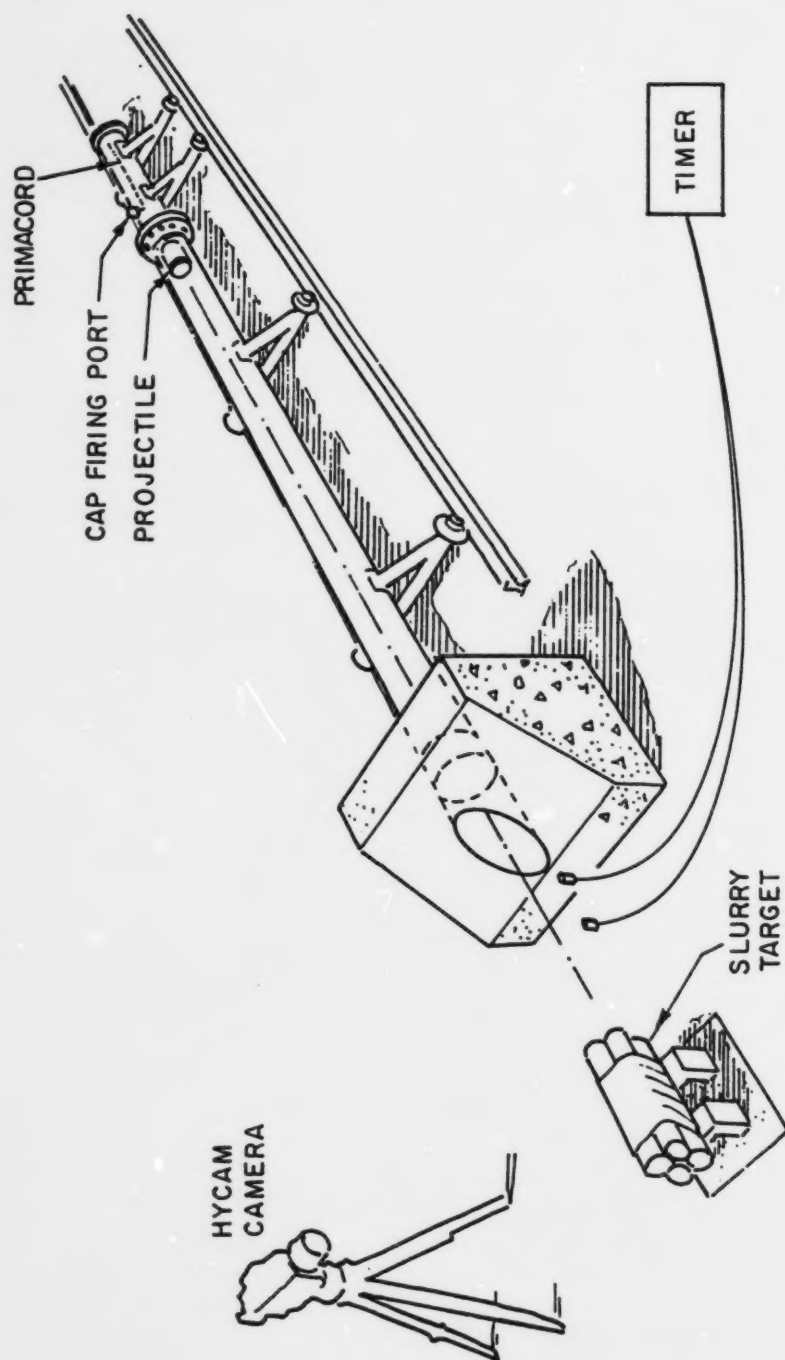


FIGURE 38 : EXPERIMENTAL SET UP FOR THE LARGE PROJECTILE IMPACT TEST .

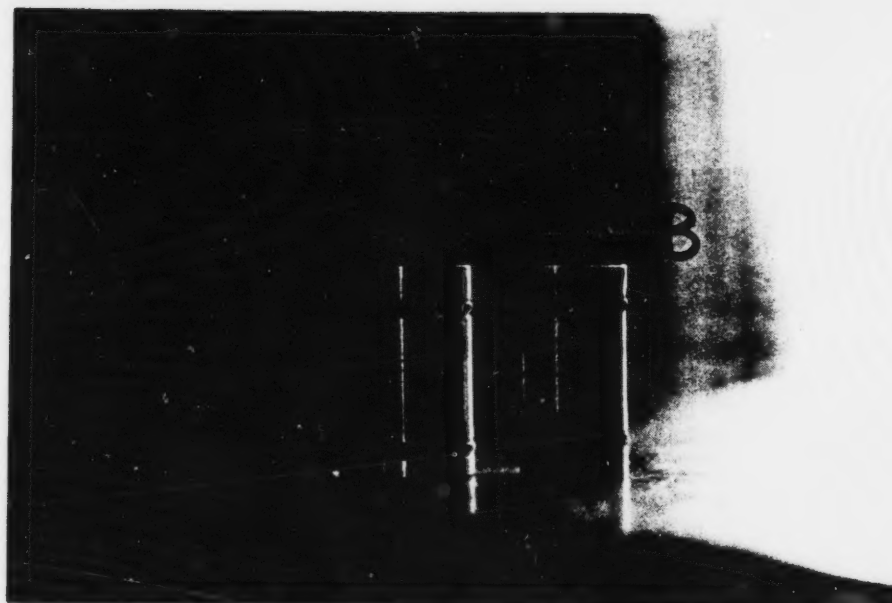
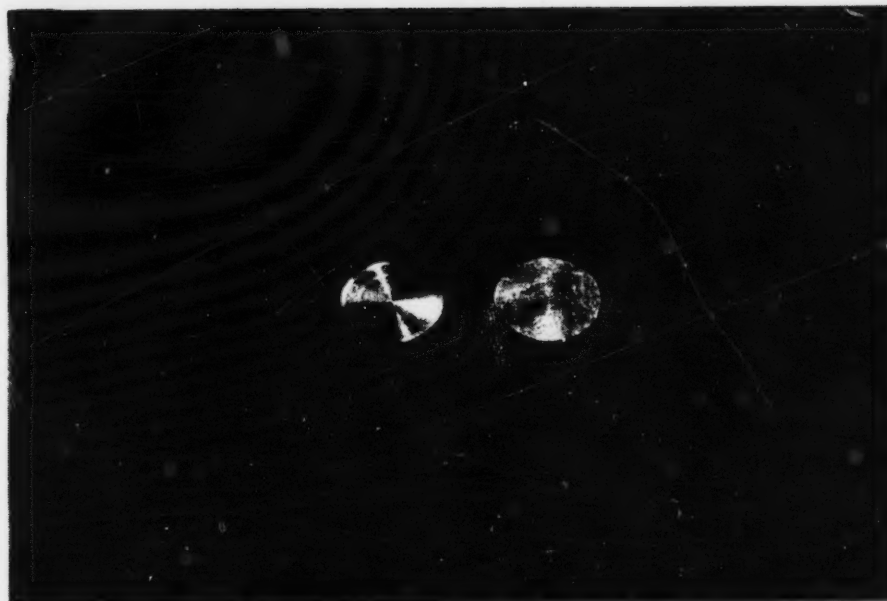


FIGURE 39: PROJECTILES (A) BEFORE IMPACT (B) AFTER IMPACT. (FAILURE)



FIGURE 40 : PROJECTILES (A) BEFORE IMPACT (B) AFTER IMPACT. (DETONATION)

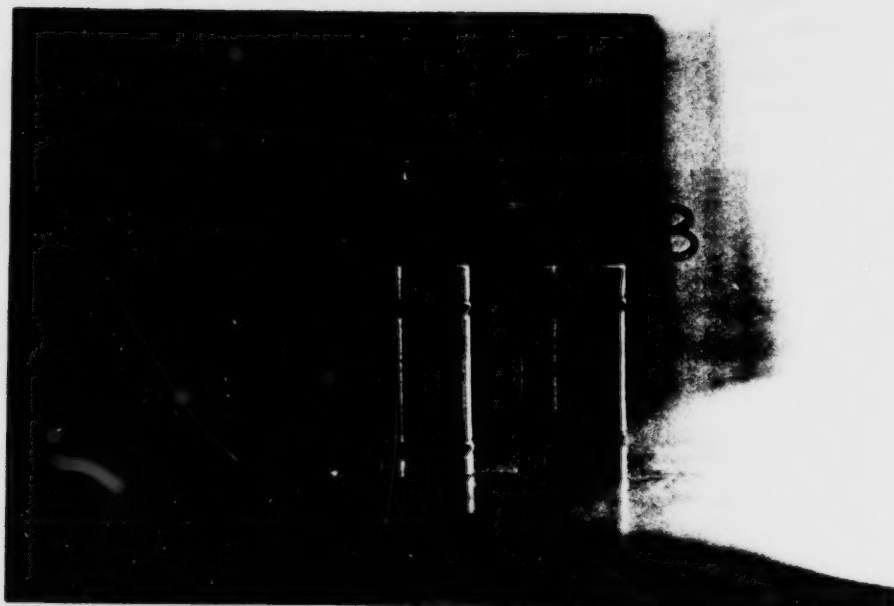


FIGURE 39: PROJECTILES (A) BEFORE IMPACT (B) AFTER IMPACT. (FAILURE)



FIGURE 40 : PROJECTILES (A) BEFORE IMPACT (B) AFTER IMPACT. (DETONATION)

**TABLE 7.1: PROJECTILE IMPACT TEST RESULTS FOR SLURRIES  
AND EMULSIONS**

| Explosive              | Projectile<br>Diameter x Length | Projectile<br>Velocity<br>(m/s) | Result    |
|------------------------|---------------------------------|---------------------------------|-----------|
| SLURRY A               | 2.5 x 5.0<br>2.5 x 5.0          | 431                             | FAILED    |
|                        |                                 | 435                             | FAILED    |
|                        |                                 | 447                             | DETONATED |
|                        |                                 | 454                             | DETONATED |
| SLURRY A               | 5 x 10                          | 146                             | FAILED    |
|                        |                                 | 152                             | DETONATED |
|                        |                                 | 194                             | DETONATED |
|                        |                                 | 208                             | DETONATED |
|                        |                                 | 239*                            | DETONATED |
| SLURRY A               | 10 x 13                         | 200                             | FAILED    |
|                        |                                 | 417                             | DETONATED |
|                        |                                 | 513                             | DETONATED |
| SLURRY B<br>unconfined | 2.5 x 5.0                       | 286                             | FAILED    |
|                        |                                 | 347                             | FAILED    |
|                        |                                 | 444                             | DETONATED |
|                        |                                 | 537                             | DETONATED |



**TABLE 7.1: PROJECTILE IMPACT TEST RESULTS FOR SLURRIES AND EMULSIONS (continued)**

| Explosive                                     | Projectile<br>Diameter x Length | Projectile<br>Velocity<br>(m/s) | Result    |
|-----------------------------------------------|---------------------------------|---------------------------------|-----------|
| SLURRY B<br>confined in<br>50mm steel<br>pipe | 2.5 x 5.0                       | 277                             | FAILED    |
|                                               |                                 | 286                             | FAILED    |
|                                               |                                 | 337                             | DETONATED |
|                                               |                                 | 356                             | DETONATED |
|                                               |                                 | 363                             | DETONATED |
| SLURRY B                                      | 5 x 10                          | 344                             | FAILED    |
|                                               |                                 | 347                             | FAILED    |
|                                               |                                 | 347                             | DETONATED |
|                                               |                                 | 350                             | DETONATED |
| SLURRY B                                      | 10 x 13                         | 337                             | FAILED    |
|                                               |                                 | 344                             | FAILED    |
|                                               |                                 | 350                             | DETONATED |
|                                               | 15 x 15                         | 219                             | FAILED    |
|                                               |                                 | 344                             | DETONATED |
|                                               |                                 | 363                             | DETONATED |
| EMULSION A                                    | 5 x 10                          | 191                             | FAILED    |
|                                               |                                 | 212                             | FAILED    |
|                                               |                                 | 223                             | FAILED    |
| EMULSION B                                    | 2.5 x 5.0                       | 494                             | FAILED    |
| EMULSION C                                    | 5 x 10                          | 190                             | FAILED    |
|                                               |                                 | 198                             | FAILED    |
|                                               |                                 | 298                             | FAILED    |
|                                               |                                 | 305                             | FAILED    |



enough to initiate most of the commercial products. The projectiles were made of brass and had a diameter and length of 13 mm. The experimental layout is shown in Figure 41. The velocity of the projectile is measured by using photocells. The results of the tests are shown in Table 7.2.

### c. Flyer Plate Impact Tests

For the cap insensitive emulsion and AN/FO a flyer plate test was designed. The flyer plate can be more effective than metal projectiles for the following reasons:

1. It can obtain higher terminal velocities. Therefore it can produce shock pulses of higher amplitude in the explosive target. According to the  $p^2t$  criterion for the impact initiation of explosives the amplitude of the shock pulse is more important than its duration.
2. The flyer plate introduces essentially a one dimensional pulse when impacting the material. This diminishes the action of side release waves which can quench the detonation.

The flyer plates were made of aluminum and were driven by detonation waves at tangential incidence. The experimental set up is shown in Figure 42. The velocity of the plate is calculated by using the Richler equation.

$$\frac{1}{\theta} = a + b (M_p/M_e) \quad (7.1)$$

where  $\theta$  is the turn angle (rads),  
 $a, b$  are constants determined for a given  
 explosive - metal plate combination and  
 $M_p/M_e$  is the mass of the plate to mass of the  
 explosive ratio.

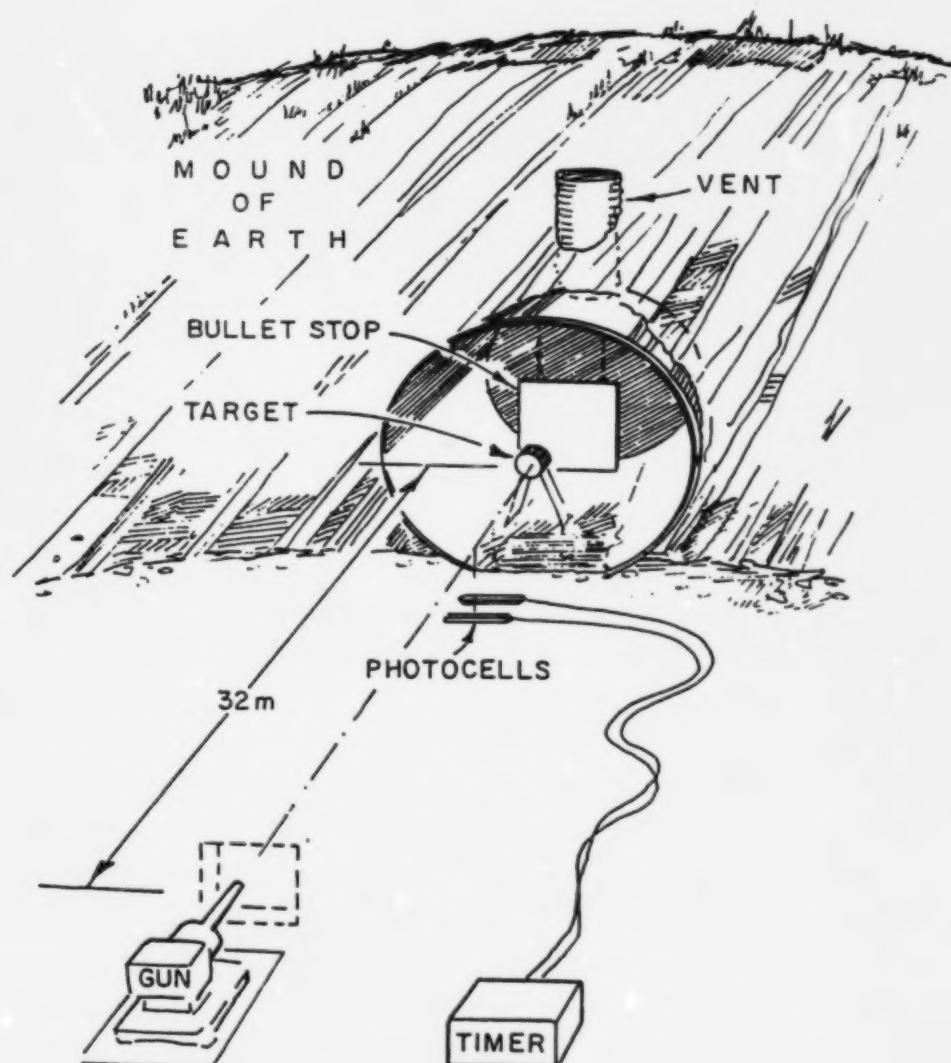


FIGURE 41: EXPERIMENTAL SET UP FOR THE HIGH VELOCITY SMALL PROJECTILE IMPACT .

TABLE 7.2: RESULTS OF THE SMALL PROJECTILE IMPACT TESTS

| EXPLOSIVE  | PROJECTILE VELOCITY<br>(m/s) | RESULT    |
|------------|------------------------------|-----------|
| EMULSION A | 856                          | DETONATED |
|            | 757                          | DETONATED |
|            | 745                          | DETONATED |
|            | 711                          | FAILED    |
|            | 707                          | FAILED    |
|            | 674                          | FAILED    |
|            | 663                          | FAILED    |
| EMULSION B | 858                          | DETONATED |
|            | 830                          | DETONATED |
|            | 802                          | FAILED    |
|            | 800                          | FAILED    |
|            | 752                          | FAILED    |
|            | 649                          | FAILED    |
| EMULSION C | 1067                         | FAILED    |
|            | 1283                         | FAILED    |
|            | 1316                         | FAILED    |

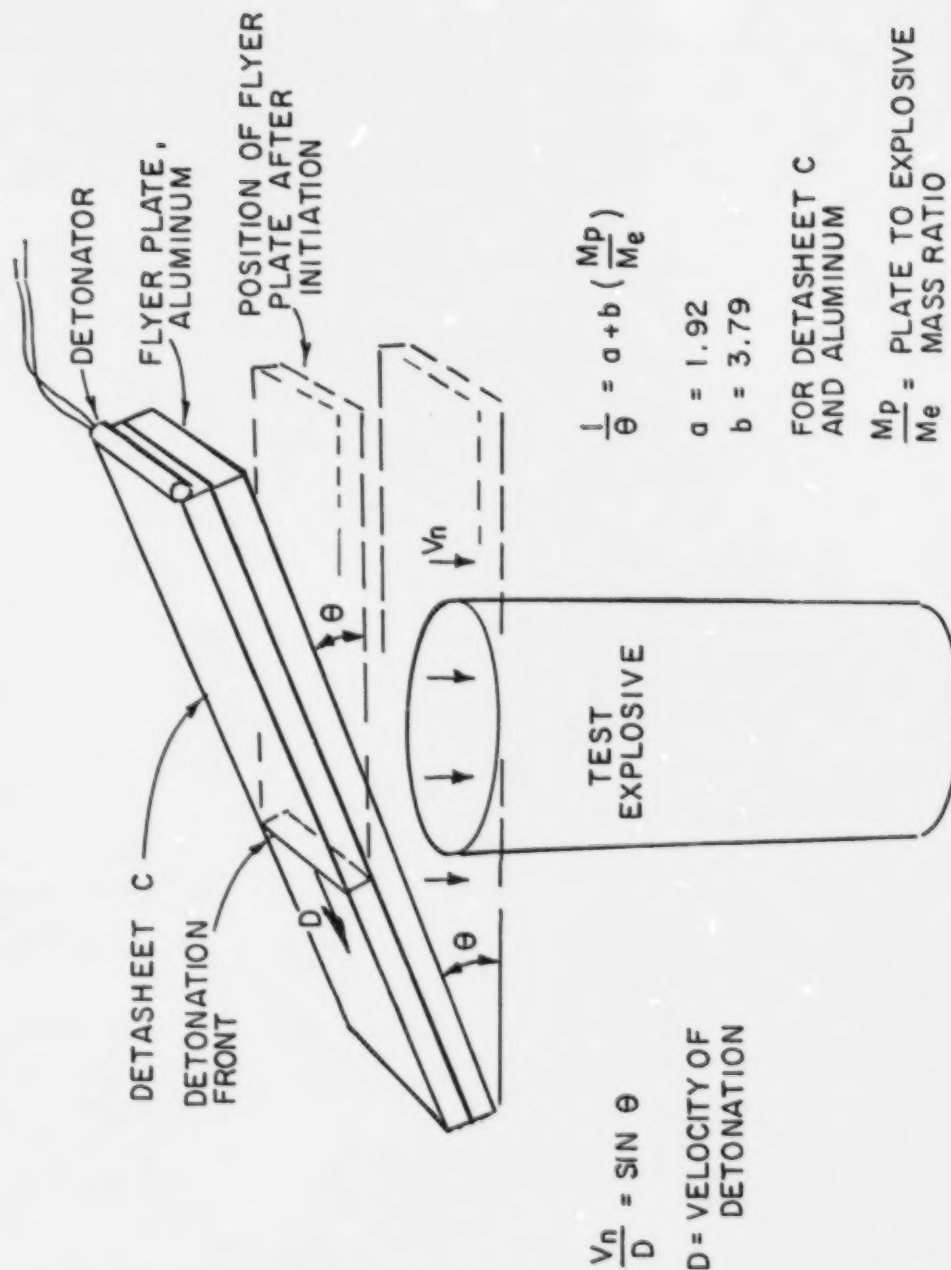


FIGURE 42 : METHOD OF PROJECTING FLYER PLATE

The constants  $a$ ,  $b$  in the above equation for the system aluminum metal plate driven by the plastic explosive Detasheet C have been determined by Belanger and Matte<sup>(2)</sup> using flash X-ray techniques. According to them  $a$  and  $b$  are 1.42 and 3.79 respectively.

The results of the flyer plate impact tests are shown in Table 7.3.

## 7.2 NUMERICAL MODELLING OF THE HIGH VELOCITY IMPACT

The numerical modelling of the high velocity impact sensitivity covered one military and six commercial explosives. The calculated results are presented in the following:

### a. Composition B

Composition B is the most common explosive fill in all types of explosive ordnance. Cast Composition B has a density of 1.713 g/c and it is not cap sensitive.

The Pop plot and the unreacted Hugoniot for Composition B have been determined by Popolato and Ramsay at the Los Alamos Laboratory. The Pop plot can be expressed as:

$$\ln X^* = -4.384 - 1.5 \ln P \quad (7.2)$$

where  $X^*$  is the distance of run to detonation (cm)  
and  $P$  is the initial pressure in the explosive  
(Mbars)

The unreacted Hugoniot for Composition B is:

TABLE 7.3: FLYER PLATE IMPACT RESULTS FOR EMULSION C AND ANFO

| EXPLOSIVE  | ALUMINUM<br>PLATE<br>THICKNESS<br>(mm) | LAYERS<br>DETASHEET<br>(number) | TURN ANGLE<br>OF PLATE<br>DETERMINED<br>BY RICHTER<br>EQ.<br>(degrees) | MP/ME<br>WEIGHT<br>RATIO | CALCULATED<br>PLATE<br>VELOCITY<br>(m/s) | RESULT    | DIAMETER<br>OF<br>CHARGE<br>(mm) |
|------------|----------------------------------------|---------------------------------|------------------------------------------------------------------------|--------------------------|------------------------------------------|-----------|----------------------------------|
| EMULSION C | 3.2                                    | 1                               | 10.2                                                                   | .98                      | 1230                                     | FAILED    | 75                               |
|            | 3.2                                    | 2                               | 15.1                                                                   | .49                      | 1820                                     | DETONATED | 75                               |
|            | 9.5                                    | 5                               | 13.8                                                                   | .59                      | 1660                                     | DETONATED | 75                               |
| ANFO       | 9.5                                    | 5                               | 13.8                                                                   | .59                      | 1660                                     | DETONATED |                                  |
|            | 9.5                                    | 2                               | 7.6                                                                    | 1.47                     | 924                                      | DETONATED |                                  |
|            | 9.5                                    | 1                               | 4.4                                                                    | 2.94                     | 531                                      | FAILED    |                                  |
|            | 12.0                                   | 1                               | 3.4                                                                    | 3.92                     | 414                                      | FAILED    |                                  |

$$U_s = 2310 + 1.83 U_p \quad (7.3)$$

where  $U_s$  is the shock velocity (m/s) and  
 $U_p$  is the particle velocity (m/s)

The reaction Hugoniot for this explosive can be expressed as<sup>(10)</sup>:

$$U_s = 2310 + 2.5 U_p \quad (7.4)$$

The HOM parameters for the unreacted material and the reaction products as calculated by Mader are presented in Table 7.4.

The Forest Fire rate coefficients are presented in Table 7.5.

By using "HYDREL" the high velocity impact of Composition B by flyer plates and small projectiles was modelled.

In the case of flyer plate initiation it was assumed that a slab of explosive was impacted by a metal plate. For the modelling, the slab and the plate were divided in quadrilateral cells of small size. The edges were assumed free to move. The relative position of the plate and the explosive is shown in Figure 43.

Trott and Jung<sup>(27)</sup> have reported the effect of the driver thickness on Composition B when it is impacted by an aluminum plate. The experimental and the calculated results are summarized in Table 7.6. Figures 44 to 51 present the computer results as pressure time and corresponding mass fraction of reacted explosive-time histories for different points of the grid. The interface between the explosive slab and the aluminum



TABLE 7.4: HOM EQUATION OF STATE PARAMETERS FOR COMPOSITION B

| <u>UNREACTED EXPLOSIVE</u> |   |                   | <u>DETONATION PRODUCTS</u> |   |                   |
|----------------------------|---|-------------------|----------------------------|---|-------------------|
| C                          | = | 2.3100000 E - 01  | A                          | = | -3.5258489 E + 00 |
| S                          | = | 1.8300000 E - 01  | B                          | = | -2.3342919 E + 00 |
| F                          | = | -8.8675078 E 00   | C                          | = | 5.9726733 E - 01  |
| G                          | = | -7.9735471 E + 01 | D                          | = | 3.0451042 E - 03  |
| H                          | = | -1.5942897 E + 02 | E                          | = | -1.7522640 E - 01 |
| I                          | = | -1.3541103 E + 02 | K                          | = | -1.5608768 E + 00 |
| J                          | = | -3.9127465 E + 01 | L                          | = | 5.3312148 E - 01  |
| Y                          | = | 1.5000000 E + 00  | M                          | = | 8.0631087 E - 02  |
| CV                         | = | 2.5900000 E - 01  | N                          | = | 3.3381689 E - 03  |
| Vo                         | = | 5.8309038 E - 01  | O                          | = | -6.8439999 E - 04 |
| α                          | = | 5.0000000 E - 05  | Q                          | = | 7.5027806 E + 00  |
|                            |   |                   | R                          | = | -4.4120900 E - 01 |
|                            |   |                   | S                          | = | 1.5129263 E - 01  |
|                            |   |                   | T                          | = | 6.7788329 E - 02  |
|                            |   |                   | U                          | = | -2.4240336 E - 02 |
|                            |   |                   | V                          | = | 5.0000000 E - 01  |
|                            |   |                   | W                          | = | 1.0000000 E - 01  |



TABLE 7.5: FOREST FIRE COEFFICIENTS FOR COMPOSITION B

|          |   |               |        |
|----------|---|---------------|--------|
| $A_1$    | = | -1.0354580437 | E + 01 |
| $A_2$    | = | 4.7342744951  | E + 02 |
| $A_3$    | = | -1.6753704228 | E + 04 |
| $A_4$    | = | 4.4756746348  | E + 05 |
| $A_5$    | = | -8.4931471542 | E + 06 |
| $A_6$    | = | 1.1555934358  | E + 08 |
| $A_7$    | = | -1.1402565157 | E + 09 |
| $A_8$    | = | 8.2065910931  | E + 09 |
| $A_9$    | = | -4.2986627008 | E + 10 |
| $A_{10}$ | = | 1.6183793696  | E + 11 |
| $A_{11}$ | = | -4.2605817430 | E + 11 |
| $A_{12}$ | = | 7.4376767275  | E + 11 |
| $A_{13}$ | = | -7.7289848996 | E + 11 |
| $A_{14}$ | = | 3.6167775705  | E + 11 |

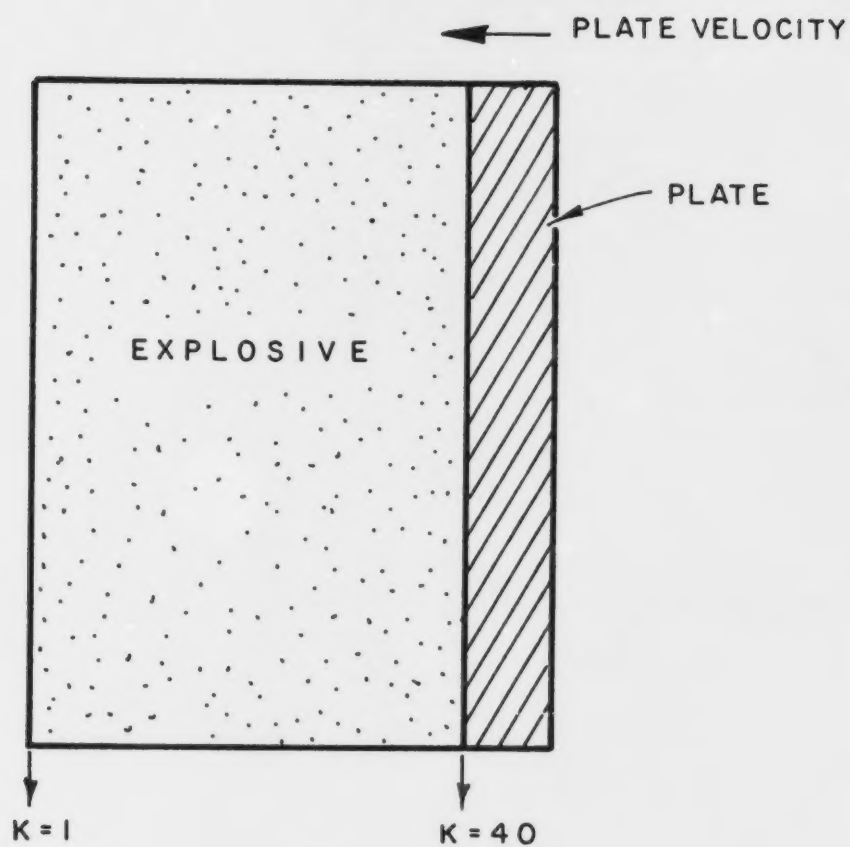


FIGURE 43: RELATIVE POSITION OF EXPLOSIVE -  
PLATE IN THE NUMERICAL MODEL

**TABLE 7.6: CALCULATED AND EXPERIMENTAL RESULTS FOR COMPOSITION B**

**COMPOSITION B**

| <b>Al PLATE THICKNESS<br/>(cm)</b> | <b>EXPERIMENTAL FAILURE<br/>VELOCITY (m/sec)</b> | <b>CALCULATED VELOCITY<br/>(m/sec) and RESULTS</b> |
|------------------------------------|--------------------------------------------------|----------------------------------------------------|
| 0.318                              | 900 - 1100                                       | 800 - failed<br>1000 - detonated                   |
| 0.102                              | 1100 - 1200                                      | 1000 - failed<br>1400 - detonated                  |

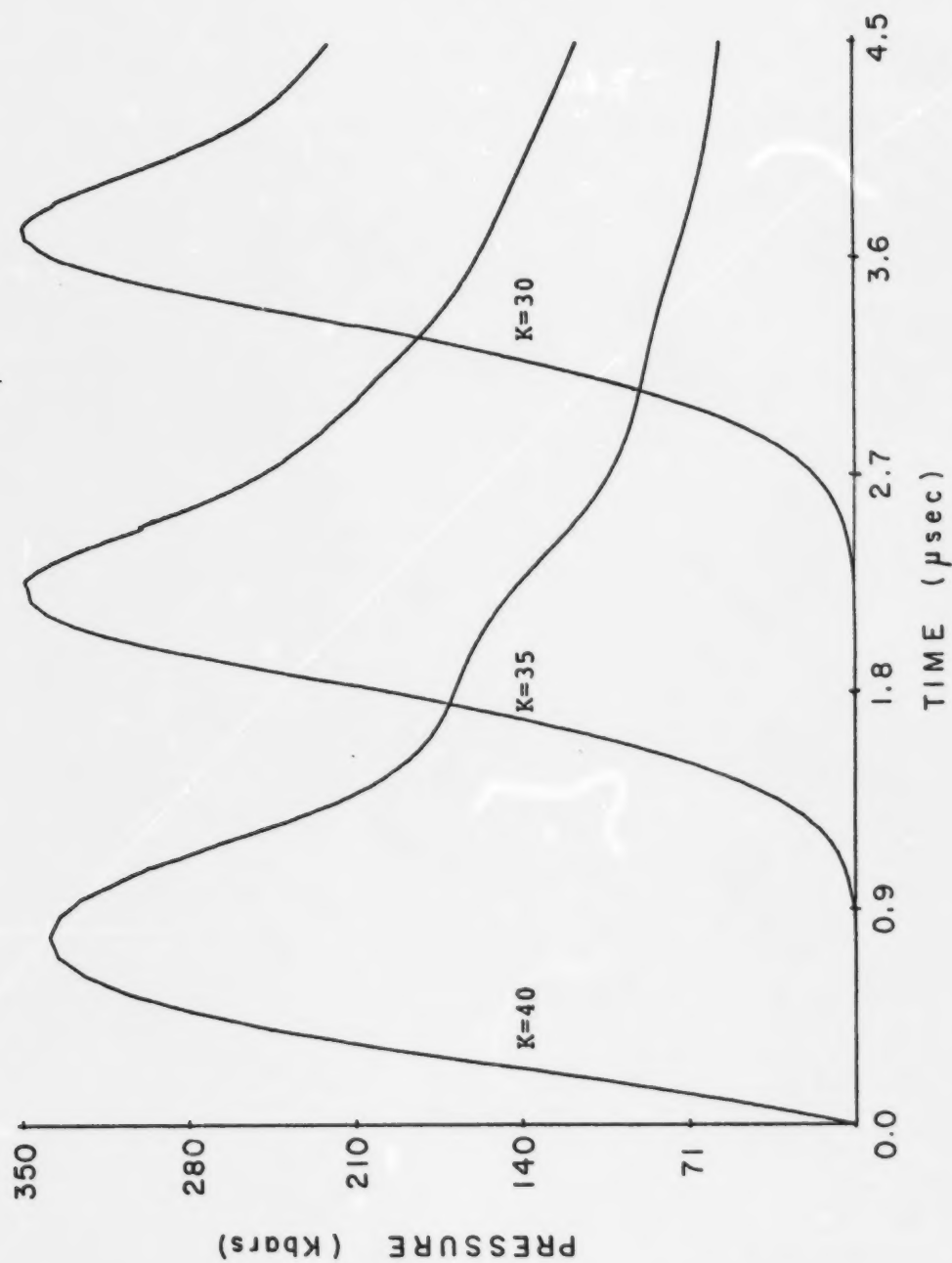


FIGURE 44 : PRESSURE-TIME HISTORIES FOR COMPOSITION B IMPACTED BY A 0.318 CM THICK ALUMINUM PLATE AT A VELOCITY OF 800 m/sec.

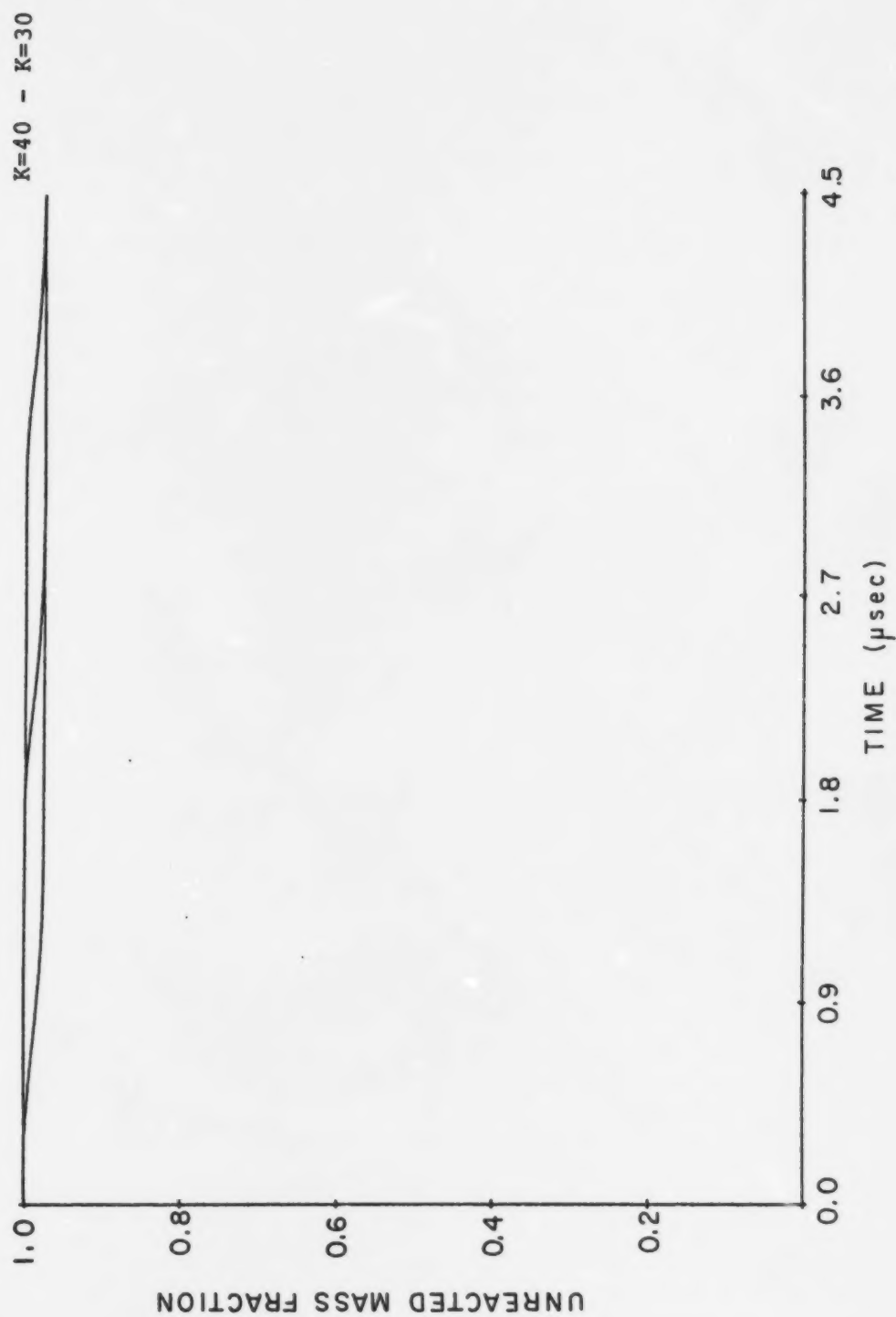


FIGURE 45 : UNREACTED EXPLOSIVE FRACTION-TIME FOR COMPOSITION B IMPACTED BY A 0.31<sup>8</sup> CM THICK ALUMINUM PLATE AT A VELOCITY OF 800 m/s.

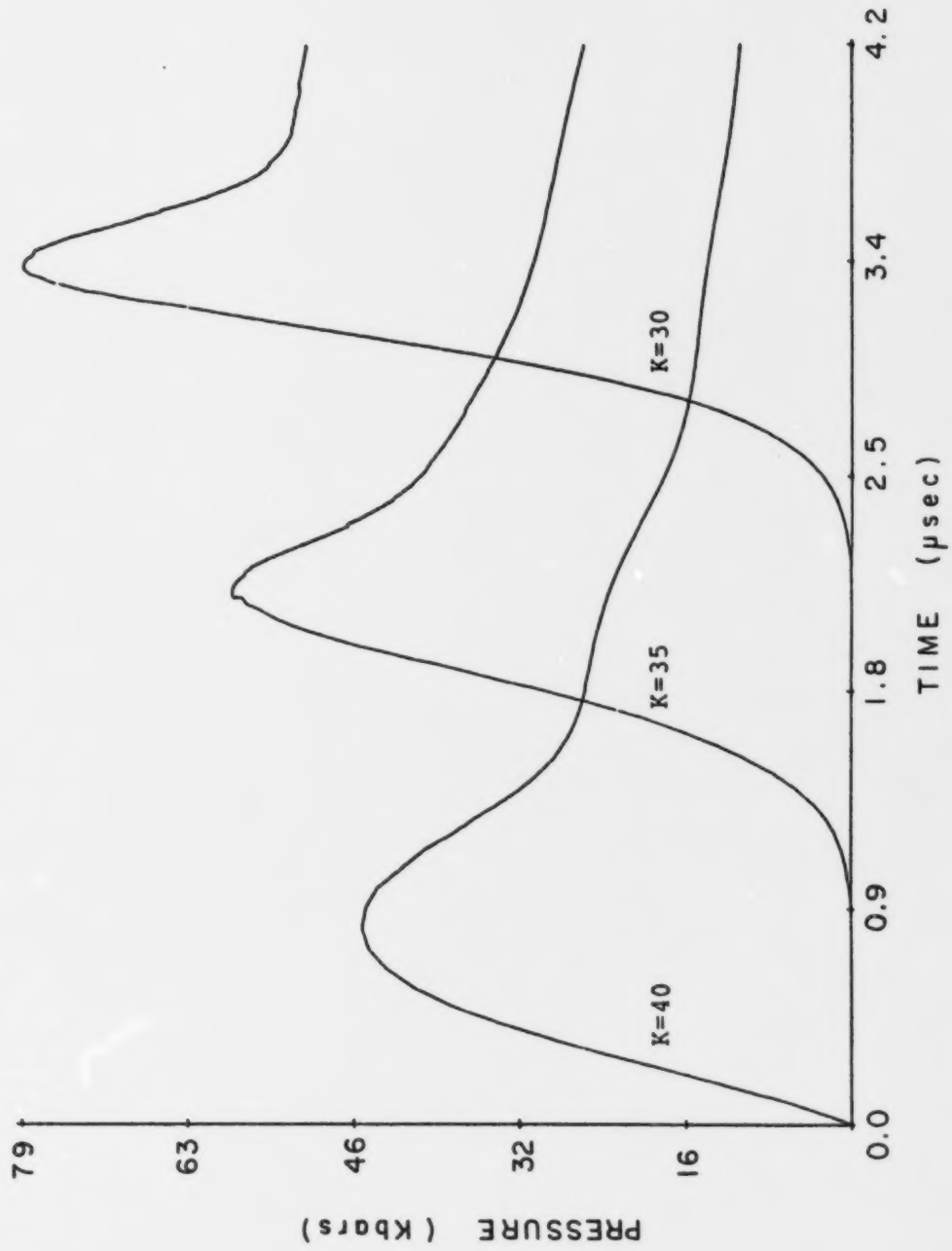


FIGURE 46: PRESSURE-TIME HISTORIES FOR COMPOSITION B IMPACTED BY A 0.318 THICK ALUMINUM PLATE AT A VELOCITY OF 1000 m/sec.

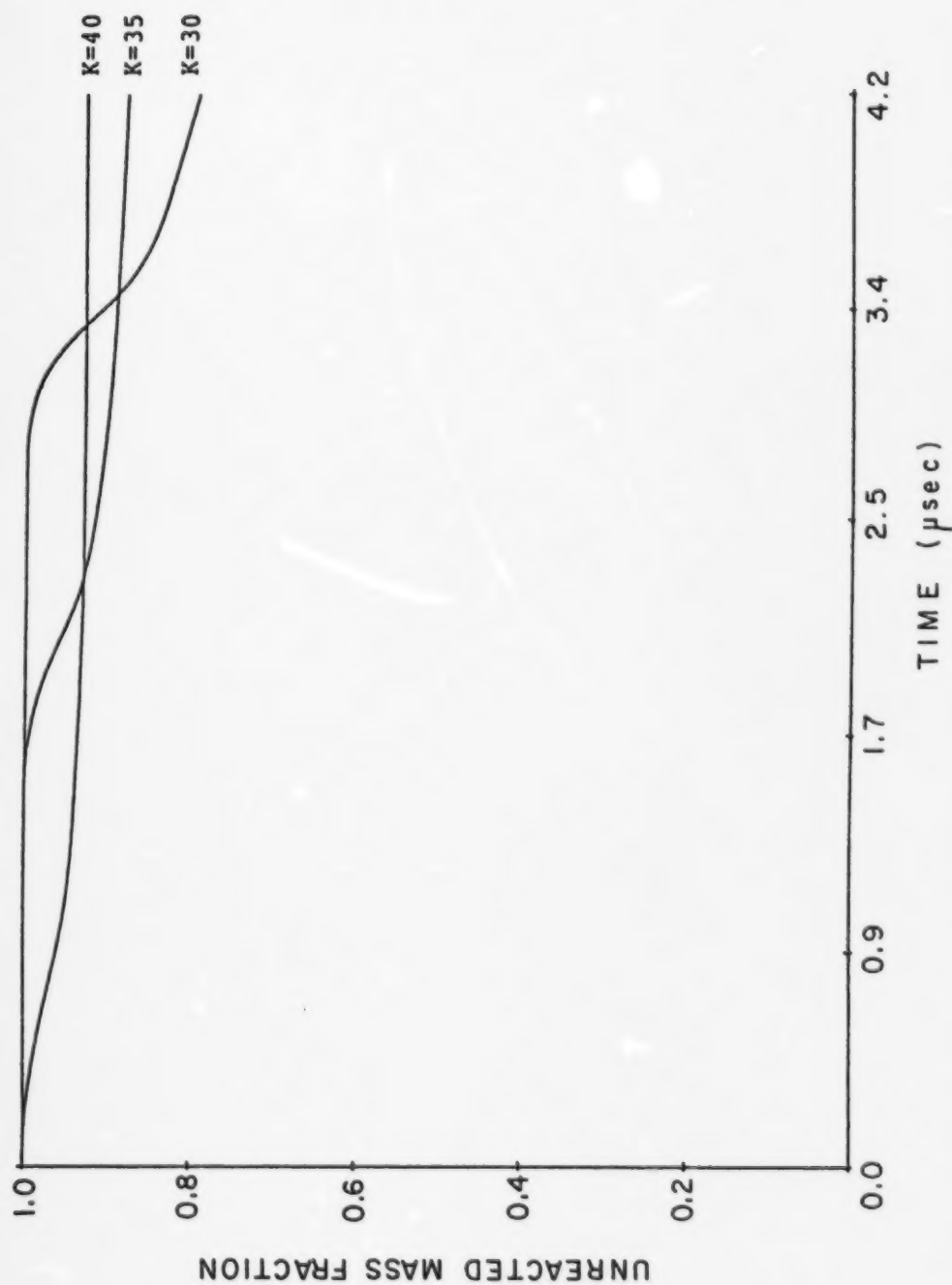


FIGURE 47 : UNREACTED EXPLOSIVE FRACTION-TIME FOR COMPOSITION B IMPACTED BY A 0.318 cm ALUMINUM PLATE AT A VELOCITY OF 1000 m/sec.

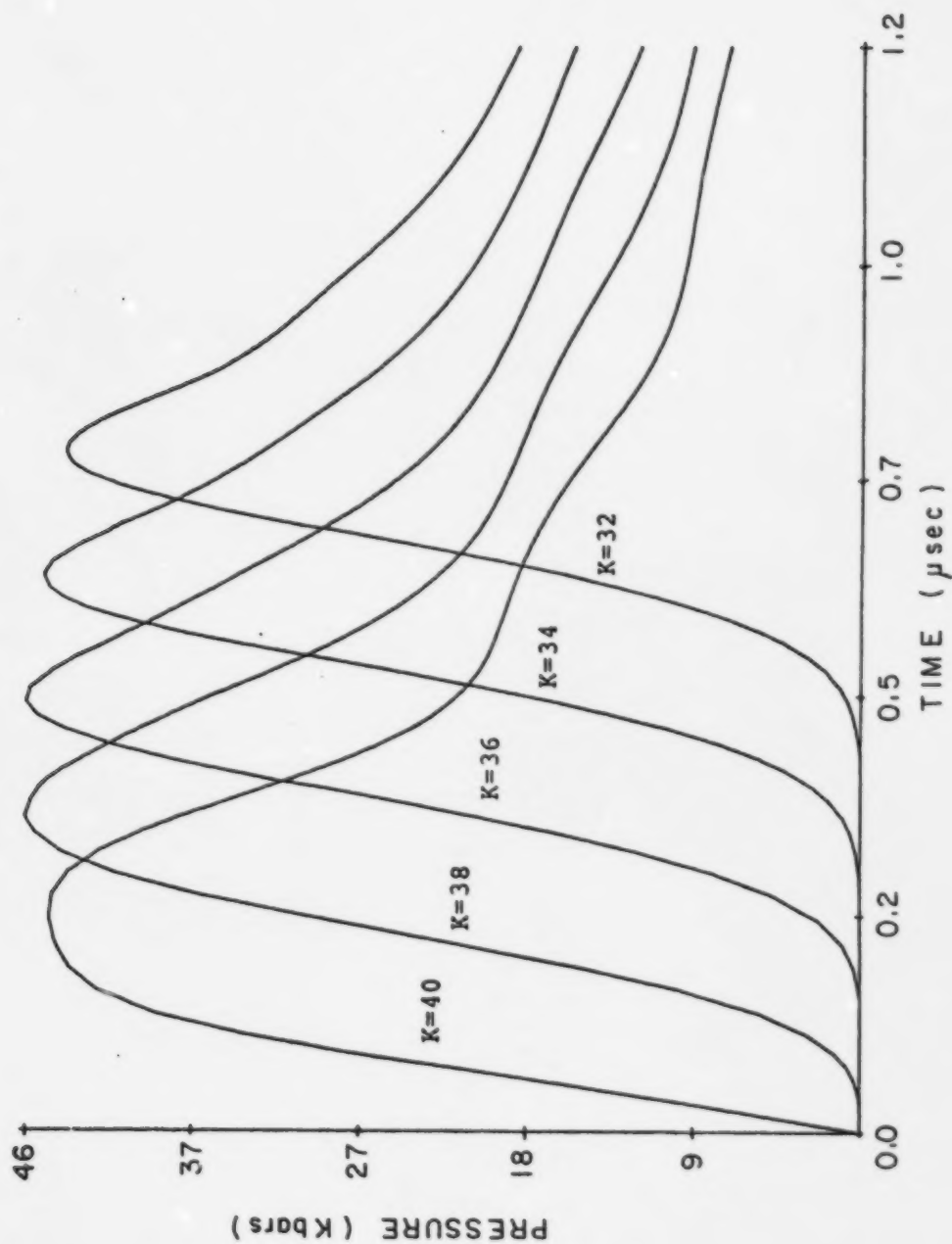


FIGURE 4S : PRESSURE-TIME HISTORIES FOR COMPOSITION B IMPACTED BY A 0.102 CM THICK ALUMINUM PLATE AT A VELOCITY OF 1000 m/sec.



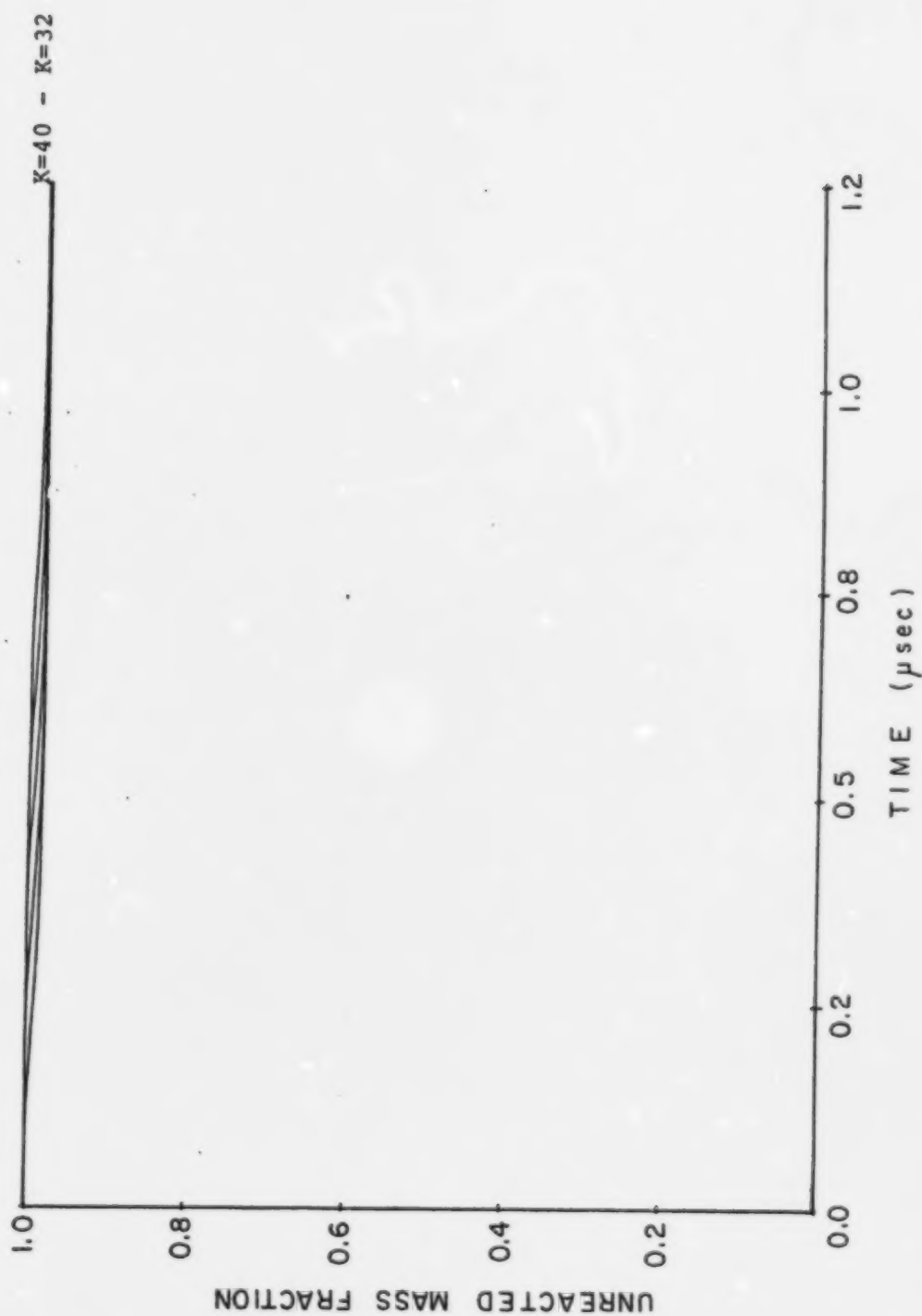


FIGURE 40: UNREACTED EXPLOSIVE FRACTION-TIME FOR COMPOSITION B IMPACTED BY A 0.102 CM THICK ALUMINUM PLATE AT A VELOCITY OF 1000 m/sec.

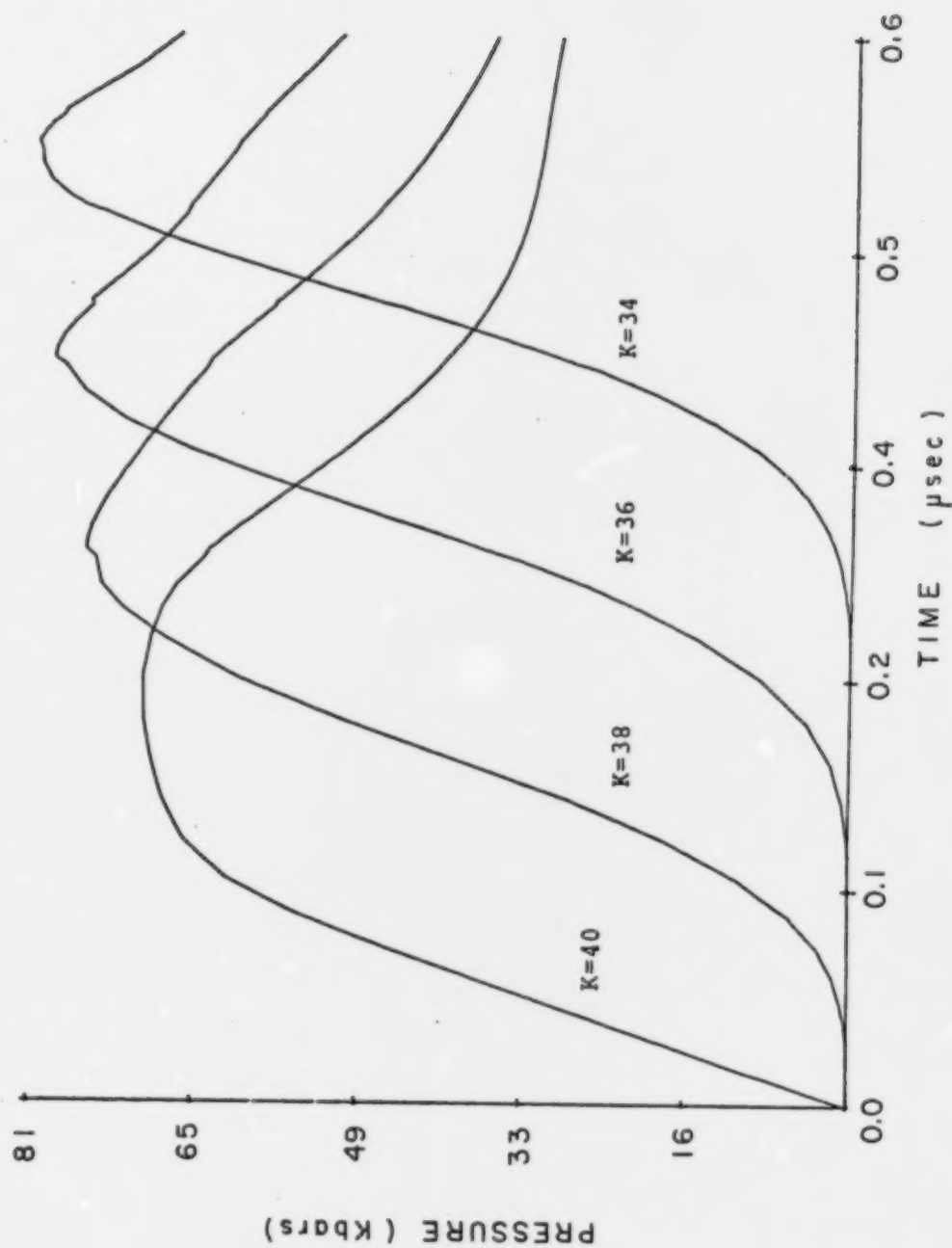


FIGURE 50: PRESSURE-TIME HISTORIES FOR COMPOSITION B IMPACTED BY A 0.102 CM THICK ALUMINUM PLATE AT A VELOCITY OF 1400 m/sec.

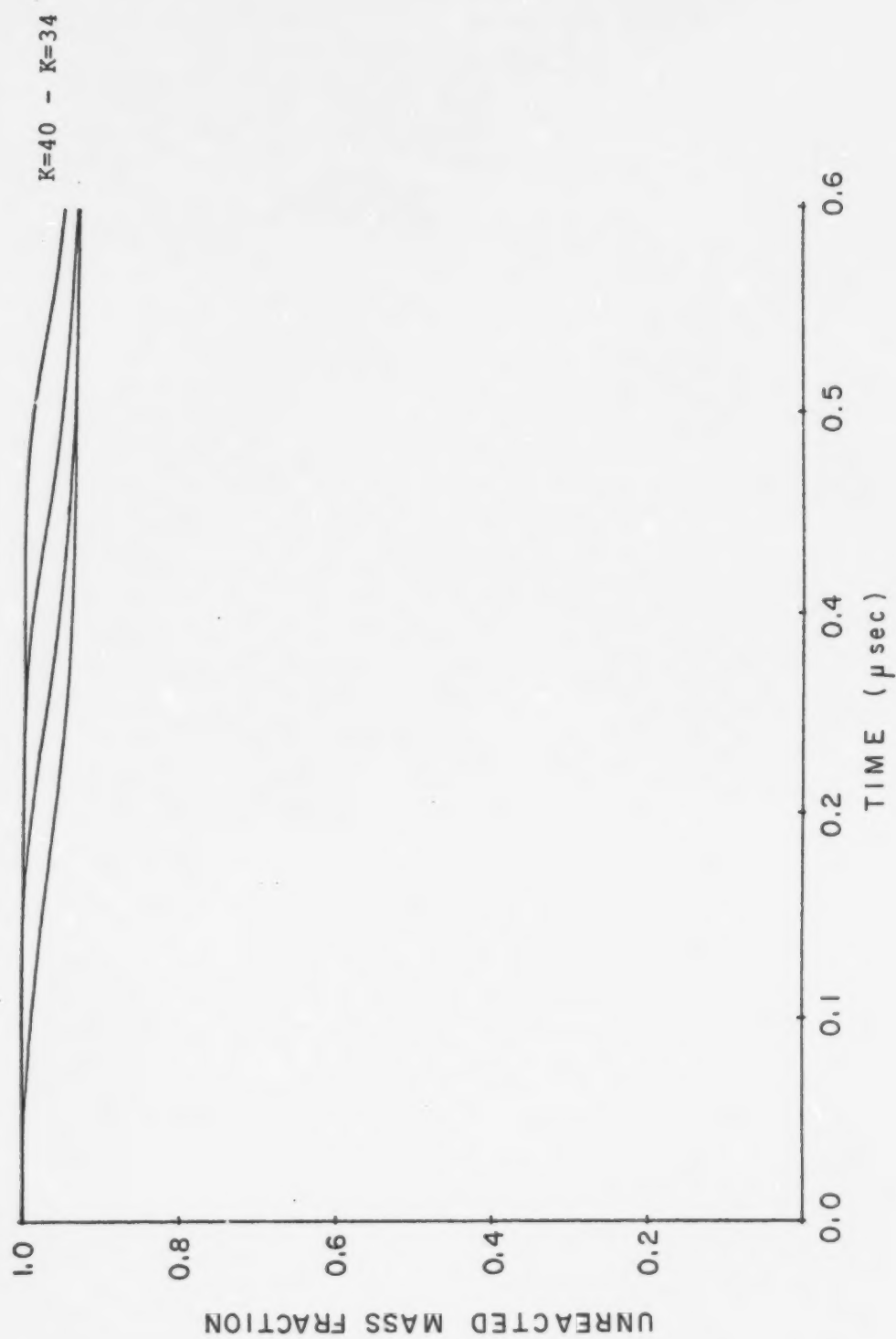


FIGURE 51: UNREACTED EXPLOSIVE FRACTION-TIME FOR COMPOSITION B IMPACTED BY A 0.102 CM THICK ALUMINUM PLATE AT A VELOCITY OF 1400 m/sec.

plate is at  $k = 40$ . Moreover the grid element size was 1 mm x 1 mm for the explosive and 0.795 mm x 1 mm for the plate for the case at the 0.318 cm thick plate and 0.25 mm x 0.25 mm for the explosive and 0.255 mm x 0.25 mm for the 1.02 mm thick plate. The HOM equation of state parameters for aluminum are shown in Table 7.7.

In order to examine the influence of the material of the plate on the impact sensitivity of Composition B results obtained for the case of a 0.318 cm thick steel plate have been included. These results are shown in Figure 52. It follows that in this case the critical velocity to initiate Composition B is below 700 m/s. This is consistent with the experimental observations<sup>(15)</sup> which indicate that the critical velocities for impact initiation of explosives are higher in the case of aluminum impactors.

Another test of the code was to compare predictions from the code against experimental results for the case of impact with small steel projectiles. Small projectiles introduce strong two dimensional phenomena on the impact. Side release waves are very important and cannot be ignored.

For the modelling it was assumed that a small cylinder of explosive was impacted by a steel projectile. The HOM equation of state parameters for steel are shown in Table 7.3. Figure 53 gives the experimental two dimensional sensitivity curve for Composition B when it is impacted by small steel projectiles. Table 7.9 summarizes the calculated and the experimental results for small projectile impacts. The element size in the numerical calculations is 0.5 mm x 0.5 mm. Figures 54 to 67 present the computer calculated results as pressure - time and corresponding mass fraction of unreacted explosive - time histories for different points of the grid. Again the interface between explosive and plate is at  $k = 40$ .

It was observed that when the projectile velocity is small

TABLE 7.7: HOM EQUATION OF STATE PARAMETERS FOR ALUMINUM

|    |     |           |        |
|----|-----|-----------|--------|
| C  | =   | 5.3500000 | E - 01 |
| C  | =   | 1.3500000 | E 00   |
| F  | = - | 7.9611587 | E + 01 |
| G  | = - | 3.1753356 | E + 02 |
| H  | = - | 4.3852537 | E + 02 |
| I  | = - | 2.6424825 | E + 02 |
| J  | = - | 5.7973496 | E + 01 |
| Y  | =   | 1.7000000 | E + 00 |
| Cv | =   | 2.2000000 | E - 01 |
| Vo | =   | 3.5906643 | E - 01 |

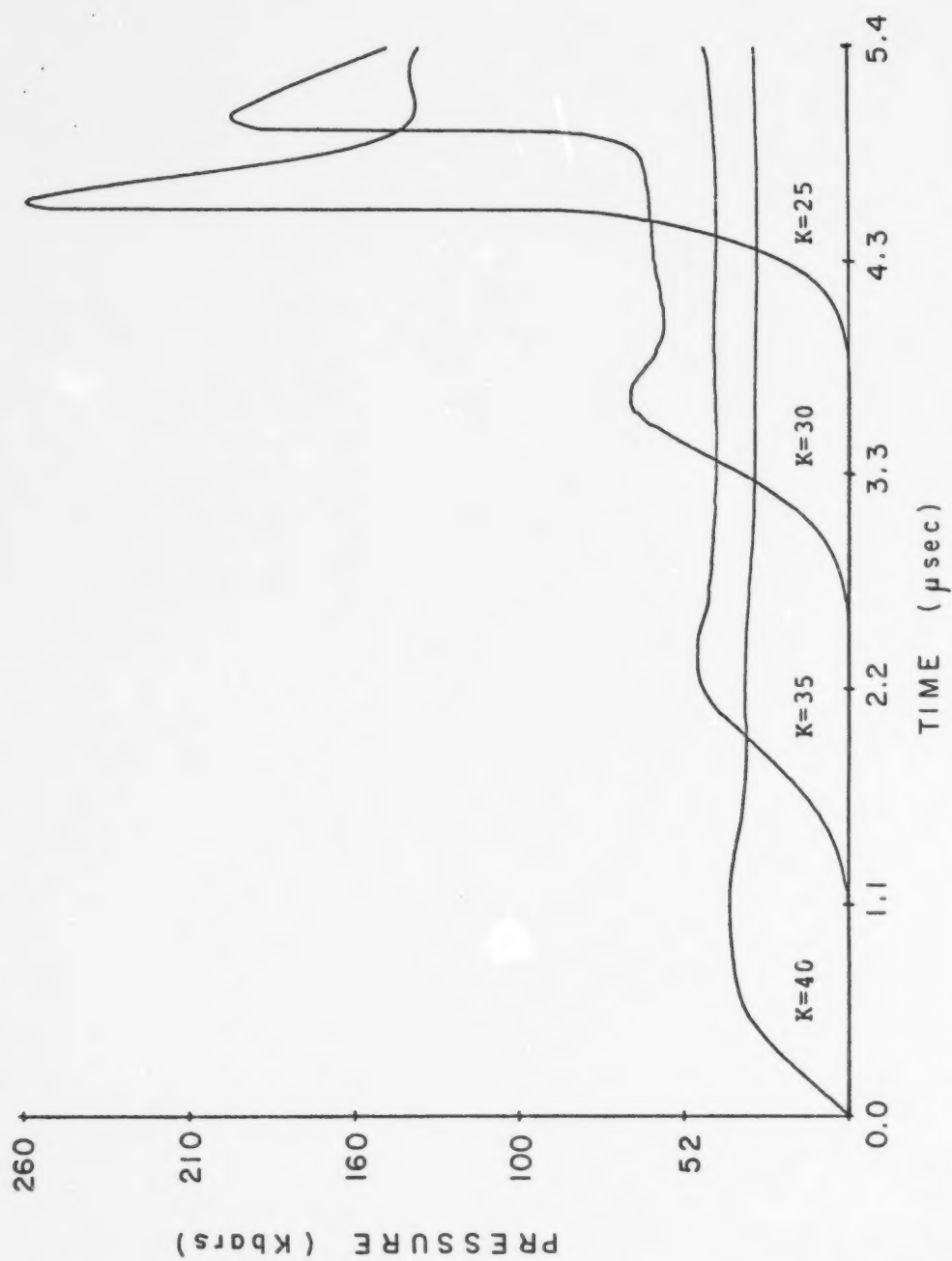


FIGURE 52: PRESSURE-TIME HISTORIES FOR COMPOSITION B IMPACTED BY A 0.318 CM THICK STEEL PLATE AT A VELOCITY OF 700 m/sec.

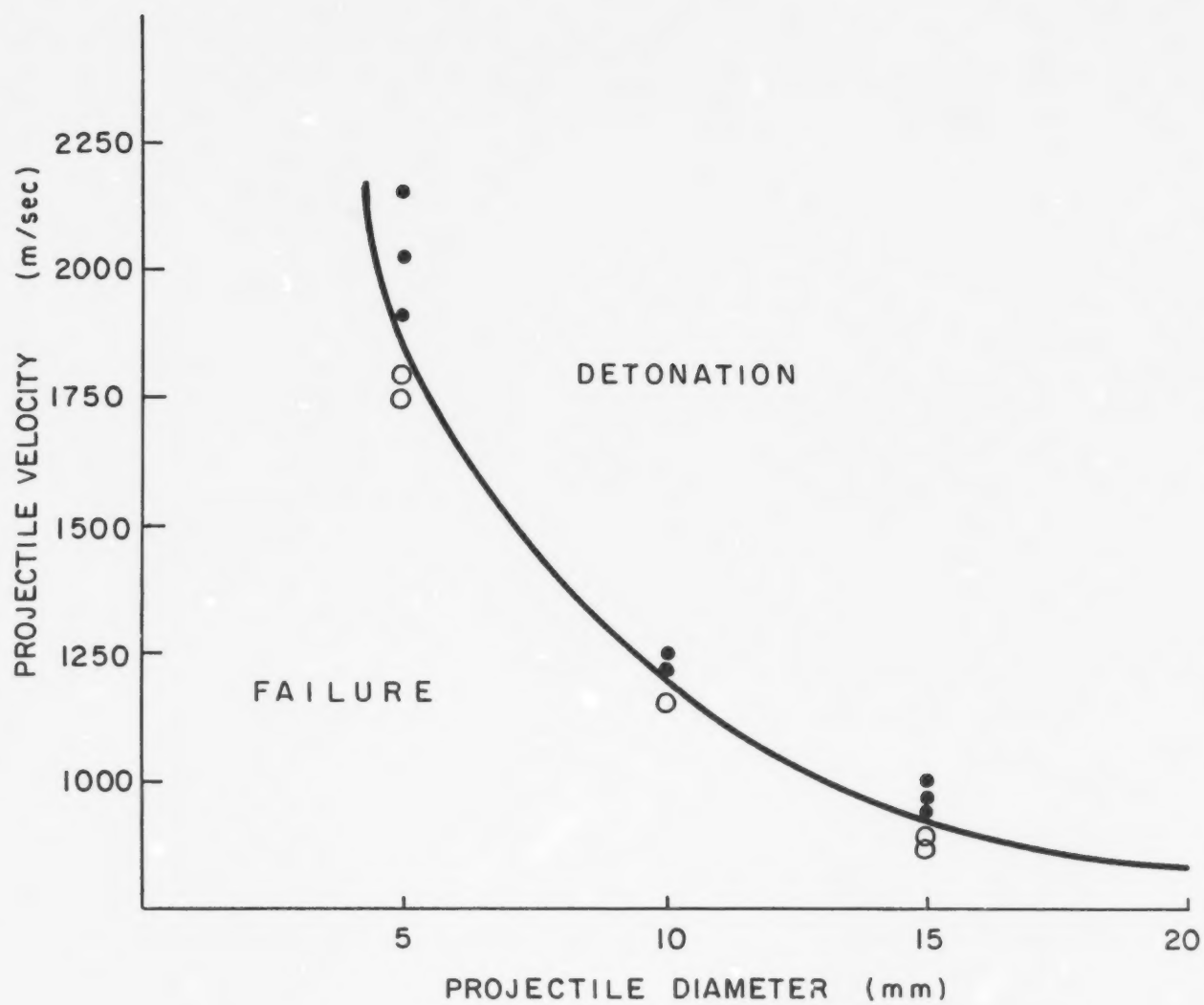


FIGURE 53: CRITICAL IMPACT VELOCITY OF SMALL STEEL PROJECTILES - PROJECTILE DIAMETER FOR COMPOSITION B .

TABLE 7. 8: HOM EQUATION OF STATE PARAMETERS FOR STEEL

|    |   |             |        |
|----|---|-------------|--------|
| C  | = | 4.5800000   | E - 01 |
| S  | = | 1.5100000   | E + 00 |
| F  | = | - 3.8238257 | E + 03 |
| G  | = | - 7.0321195 | E + 03 |
| H  | = | - 4.8267021 | E + 03 |
| I  | = | - 1.4667840 | E + 03 |
| J  | = | - 1.6639161 | E + 02 |
| Y  | = | 2.0000000   | E + 00 |
| Cv | = | 1.0700000   | E - 01 |
| Vo | = | 1.2631047   | E - 01 |
| a  | = | 1.1700000   | E - 05 |



TABLE 7.9: CALCULATED AND EXPERIMENTAL RESULTS FOR COMPOSITION B

| PROJECTILE DIAMETER<br>(mm) | EXPERIMENTAL FAILURE<br>VELOCITY (m/sec) | CALCULATED VELOCITY<br>(m/sec) and RESULTS            |
|-----------------------------|------------------------------------------|-------------------------------------------------------|
| 18                          | 820                                      | 700 - failed<br>900 - detonated                       |
| 15                          | 920                                      | 900 - failed<br>1000 - detonated                      |
| 10                          | 1204                                     | 1200 - failed<br>1300 - detonated<br>1500 - detonated |

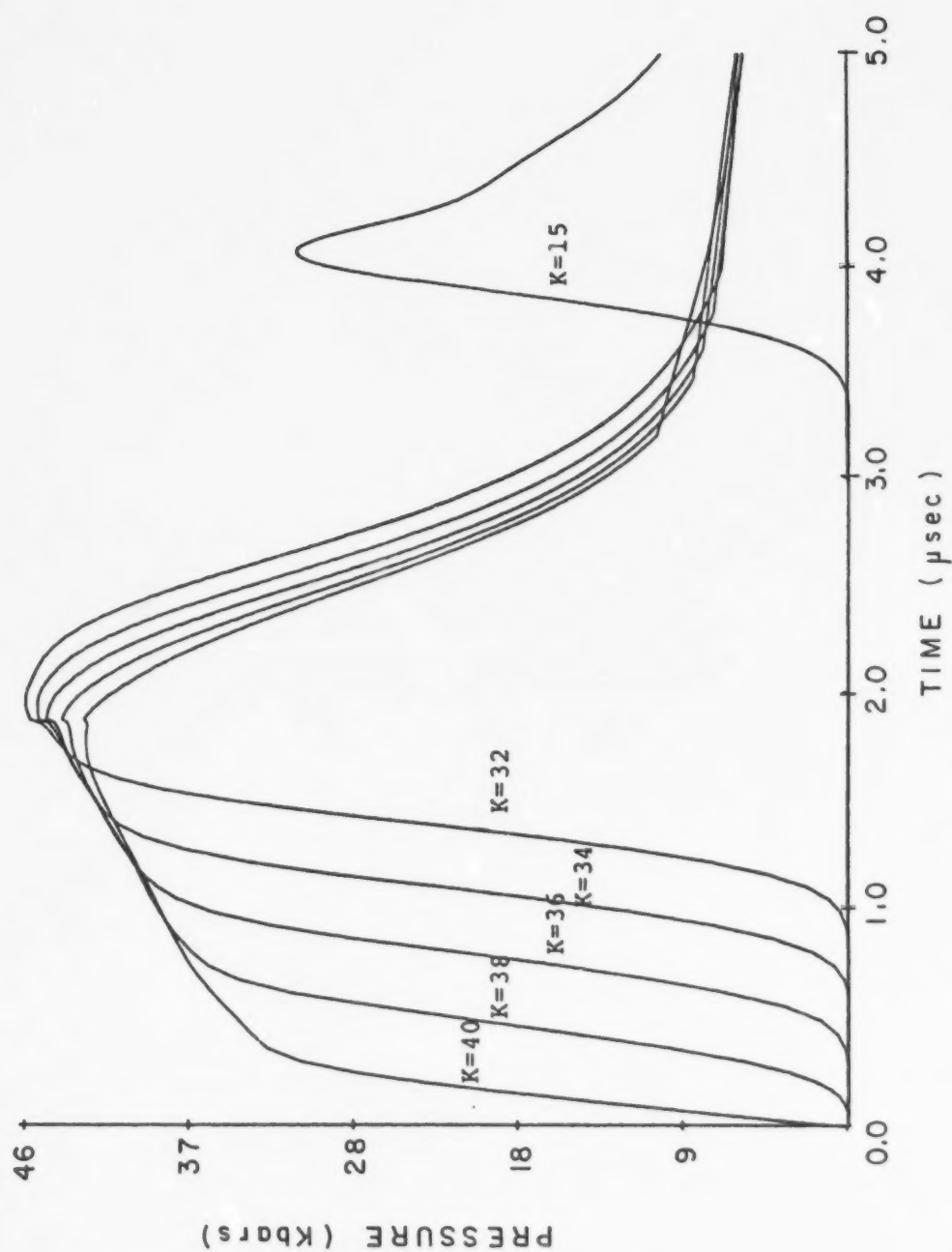


FIGURE 54 : PRESSURE-TIME HISTORIES FOR COMPOSITION B IMPACTED BY A 18 MM DIAMETER STEEL PROJECTILE AT A VELOCITY OF 700 m/s.

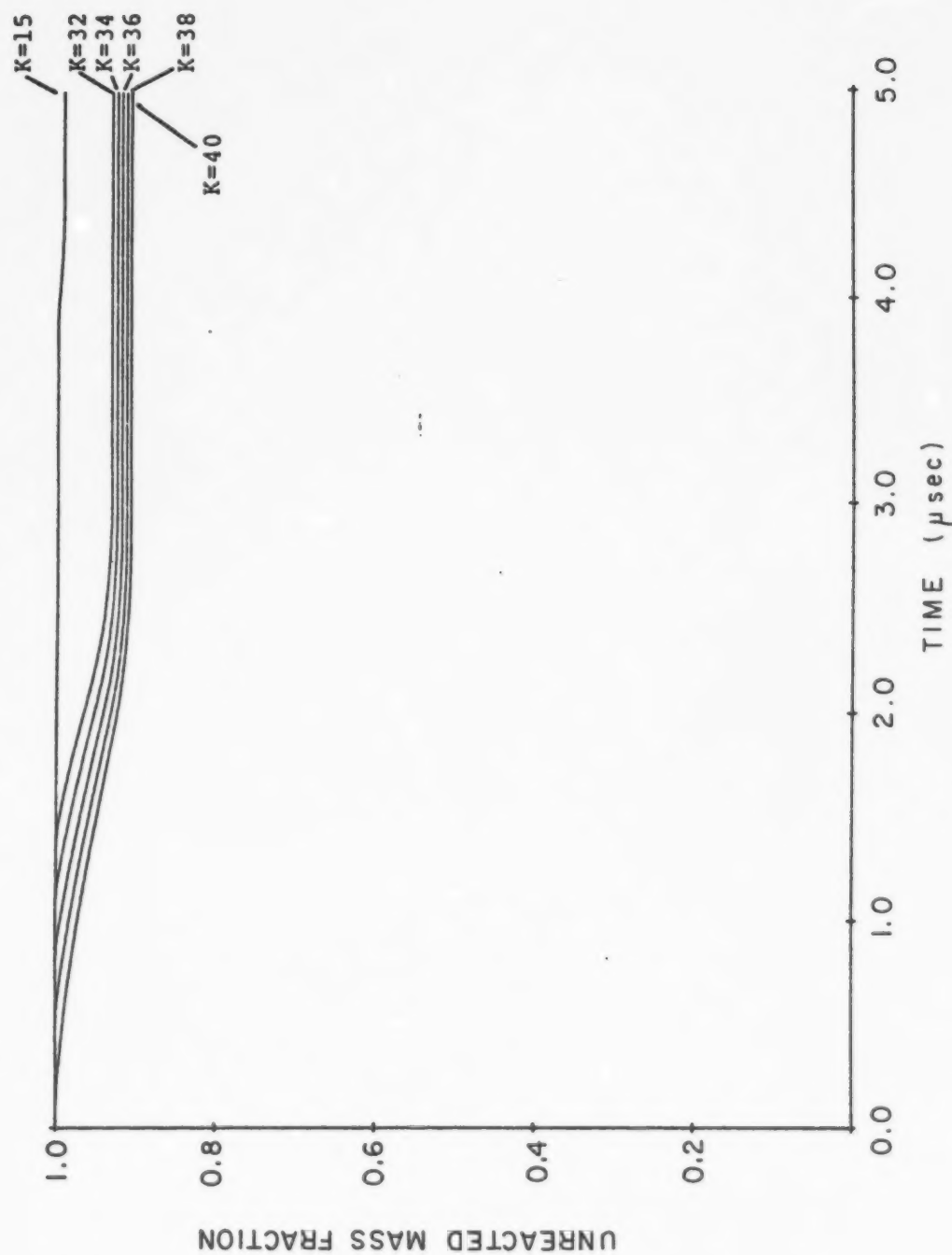


FIGURE 55: UNREACTED EXPLOSIVE FRACTION-TIME FOR COMPOSITION B IMPACTED BY A 18 MM DIAMETER STEEL PROJECTILE AT A VELOCITY OF 700 m/sec.

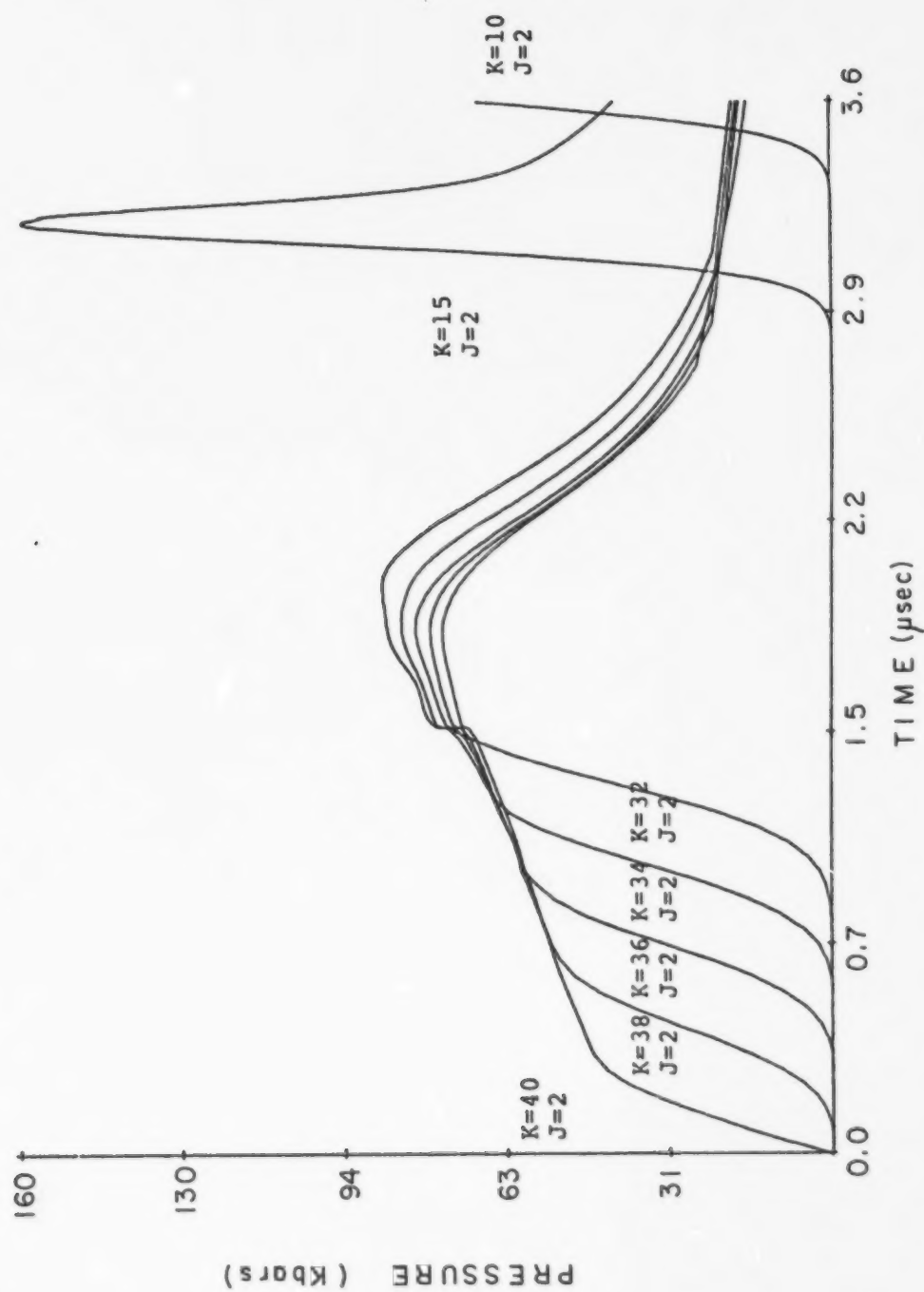


FIGURE 50: PRESSURE-TIME FOR COMPOSITION B IMPACTED BY A 18 MM DIAMETER STEEL PROJECTILE AT A VELOCITY OF 900 m/sec.

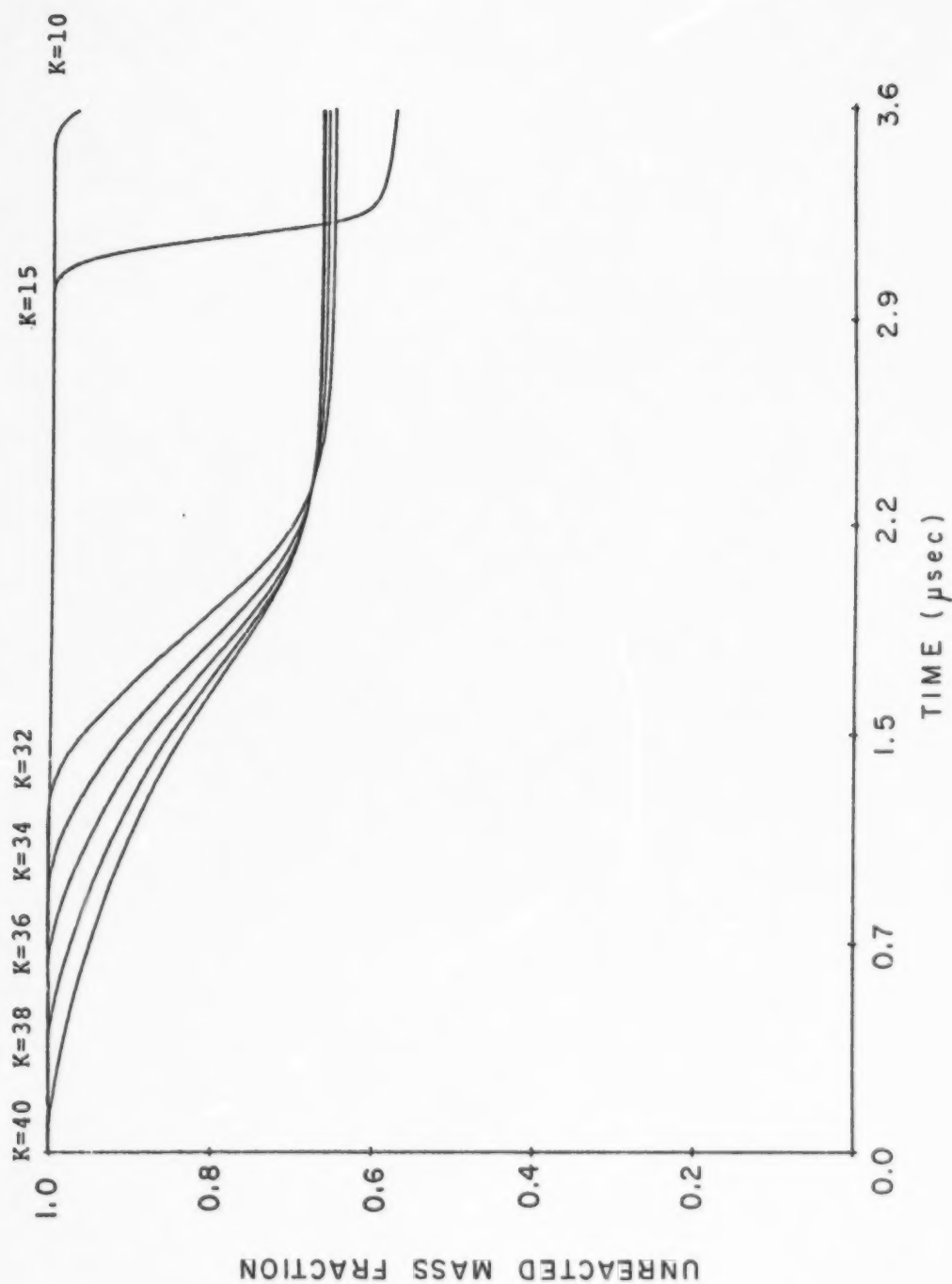


FIGURE 57 : UNREACTED EXPLOSIVE FRACTION-TIME FOR COMPOSITION B IMPACTED BY A 18 MM DIAMETER STEEL PROJECTILE AT A VELOCITY OF 900 m/sec.

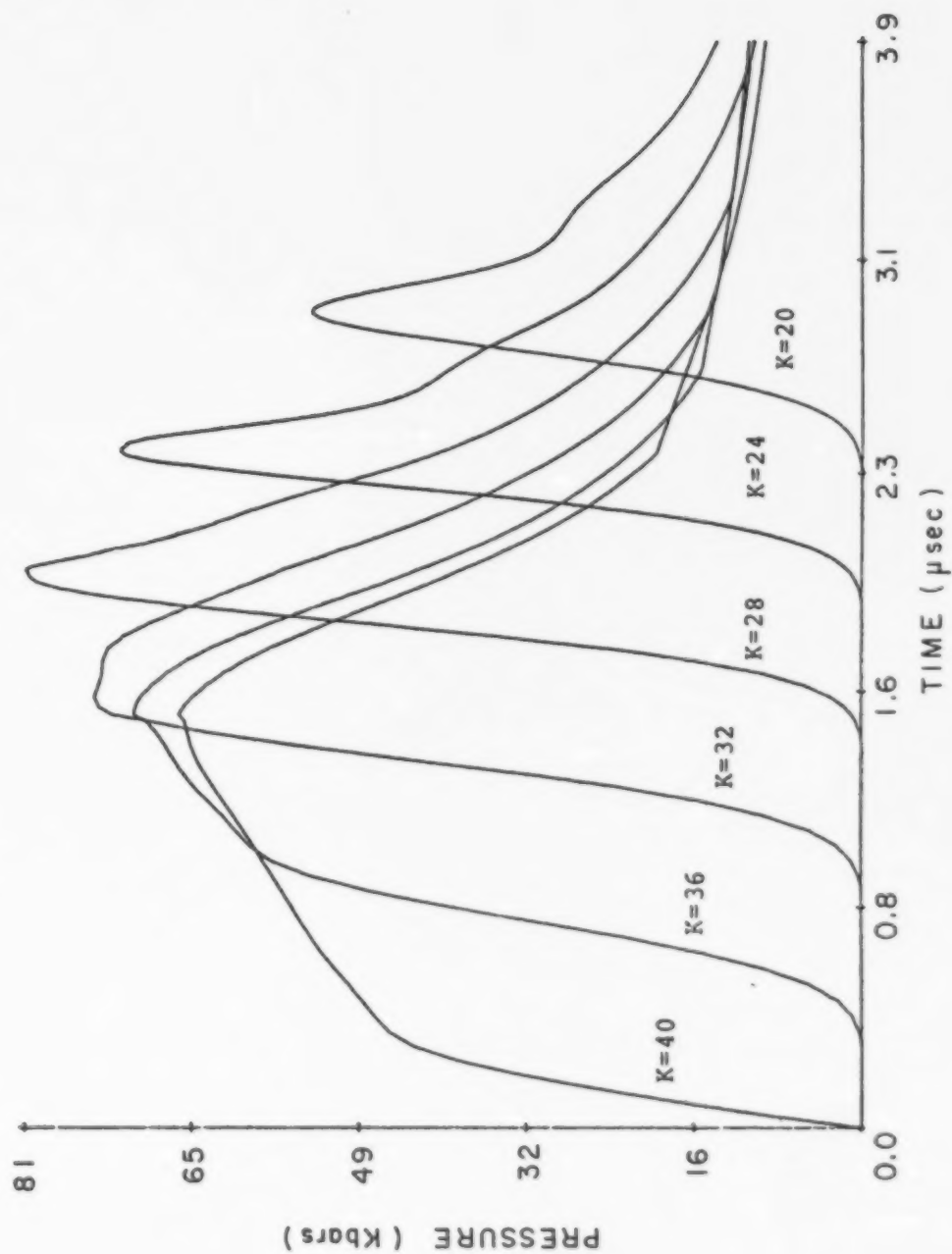


FIGURE 5: PRESSURE-TIME HISTORIES FOR COMPOSITION B IMPACTED BY A 15 MM DIAMETER STEEL PROJECTILE AT A VELOCITY OF 900 m/sec.

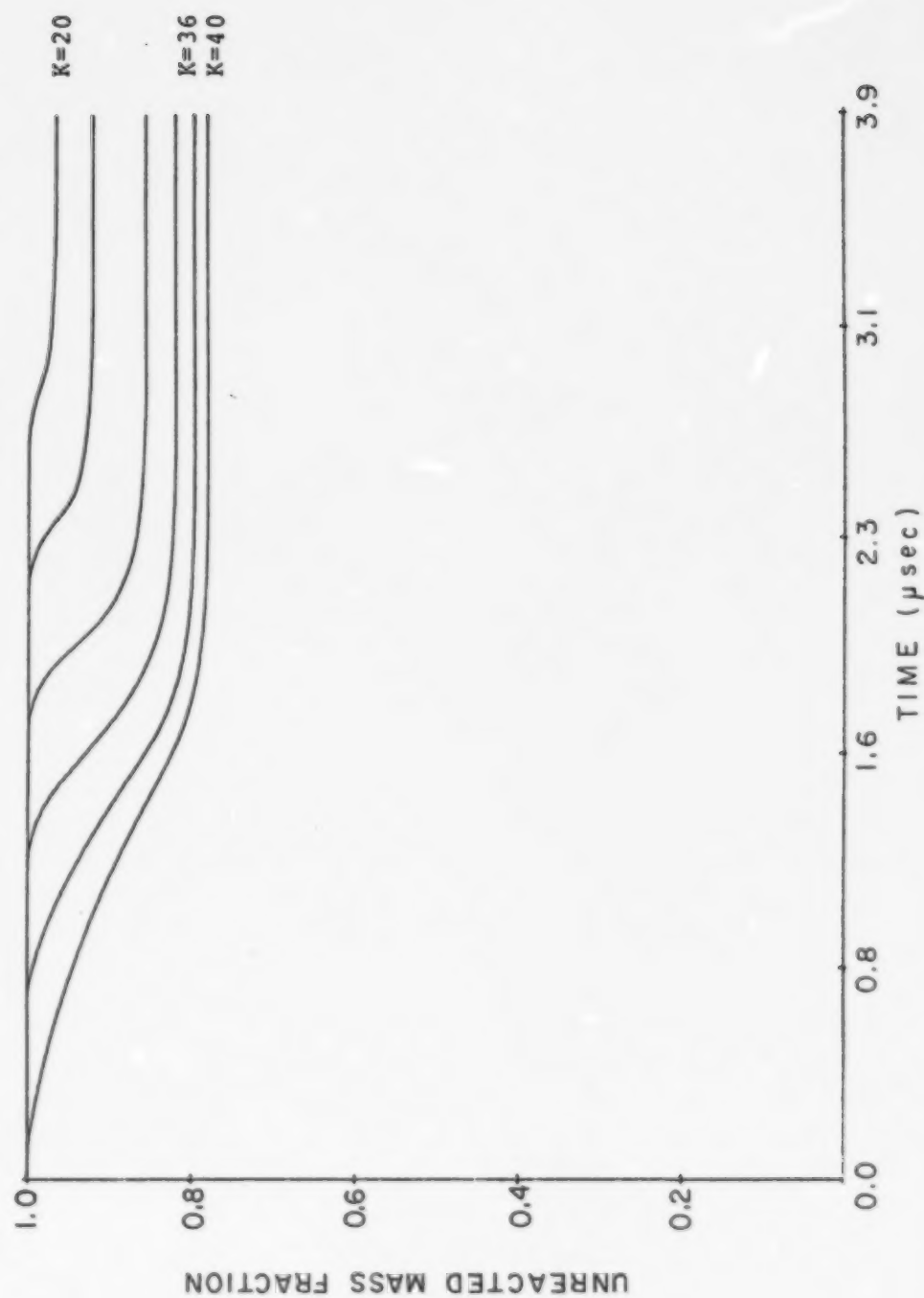


FIGURE 59 : UNREACTED EXPLOSIVE FRACTION-TIME FOR COMPOSITION B IMPACTED BY A 15 MM DIAMETER PROJECTILE AT A VELOCITY OF 900 m/sec.

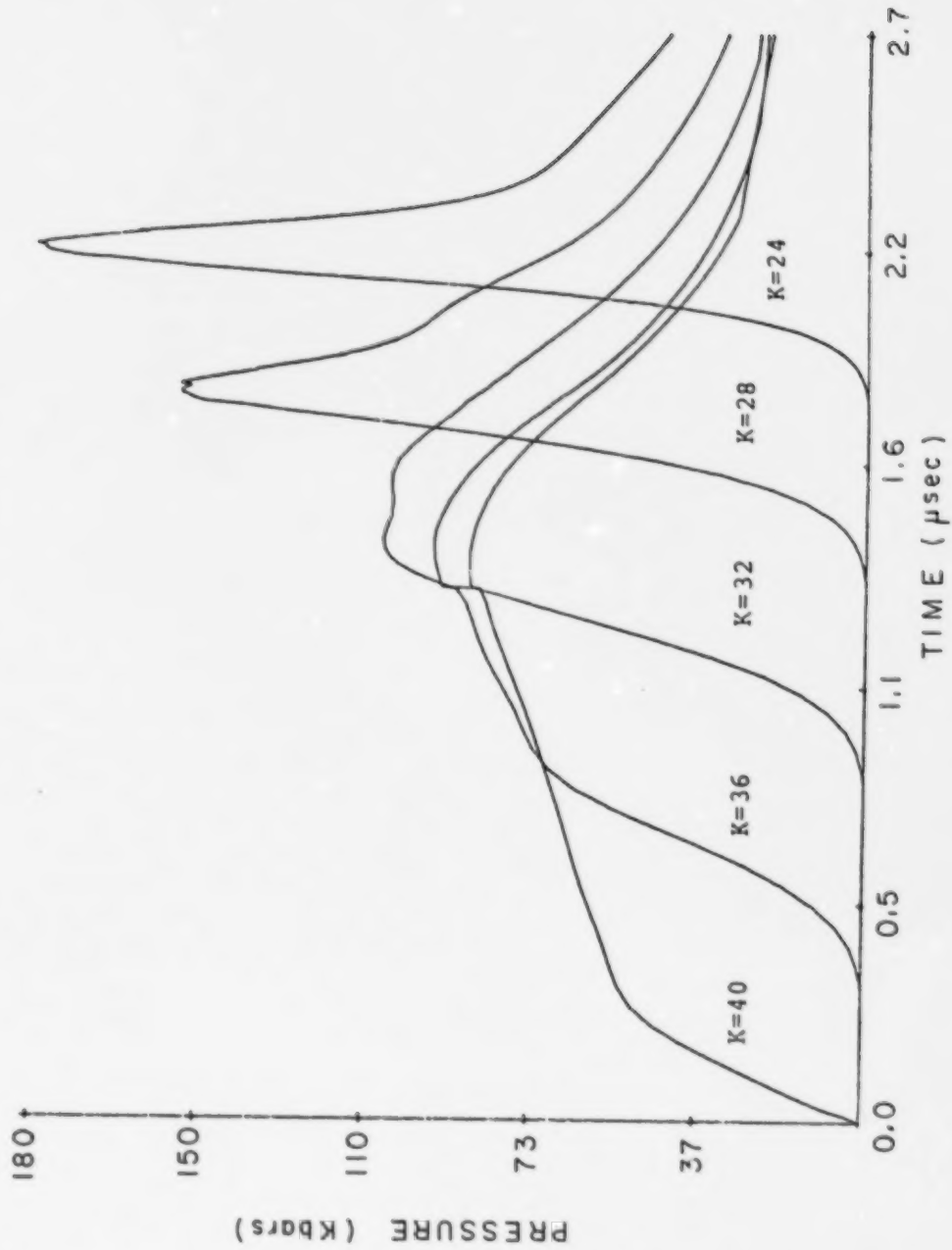


FIGURE 60: PRESSURE-TIME HISTORIES FOR COMPOSITION B IMPACTED BY A 15 MM DIAMETER STEEL PROJECTILE AT A VELOCITY OF 1000 M/SEC.



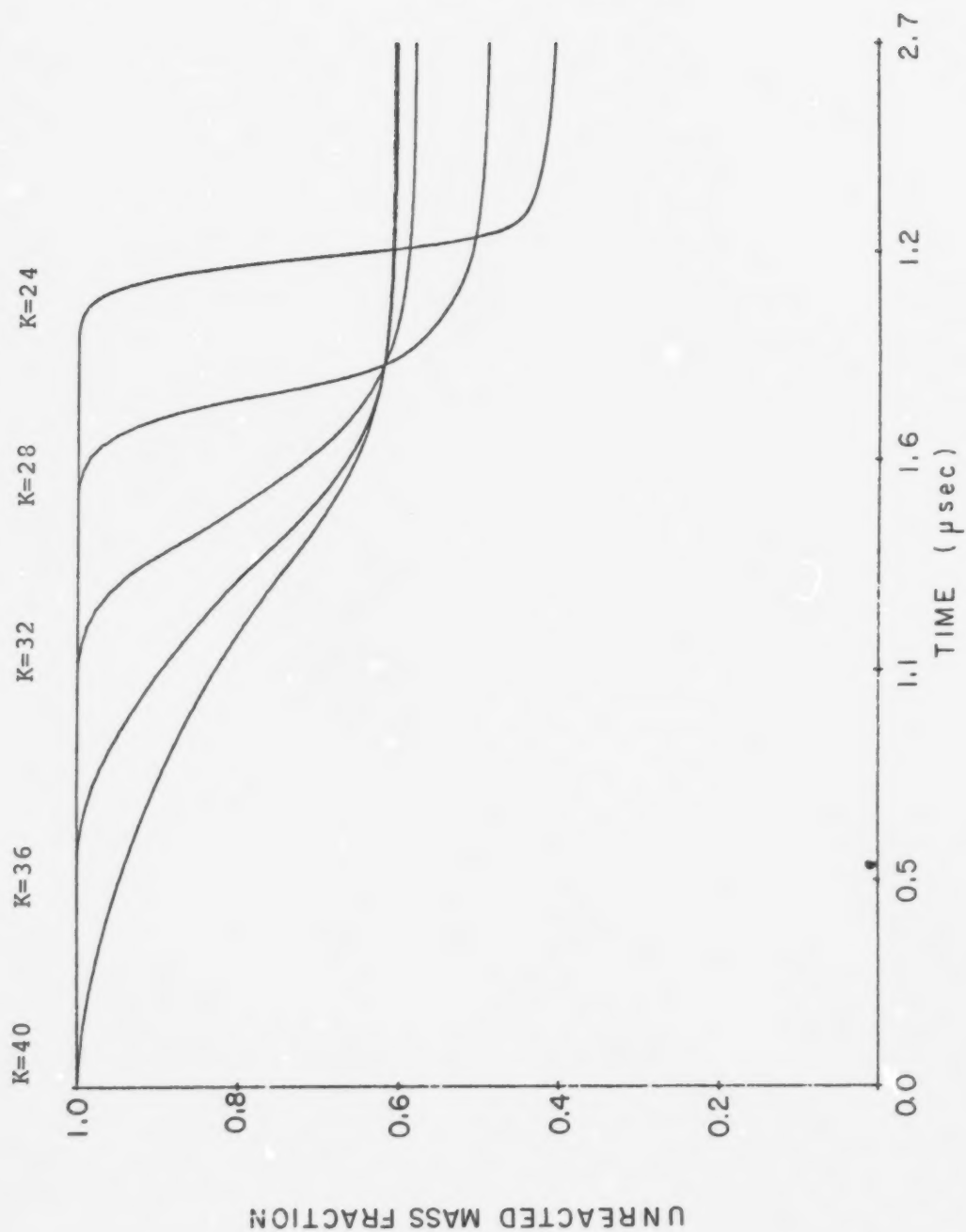


FIGURE 61: UNREACTED EXPLOSIVE FRACTION-TIME FOR COMPOSITION B IMPACTED BY A 15 MM DIAMETER STEEL PROJECTILE AT A VELOCITY OF 1000 m/sec.

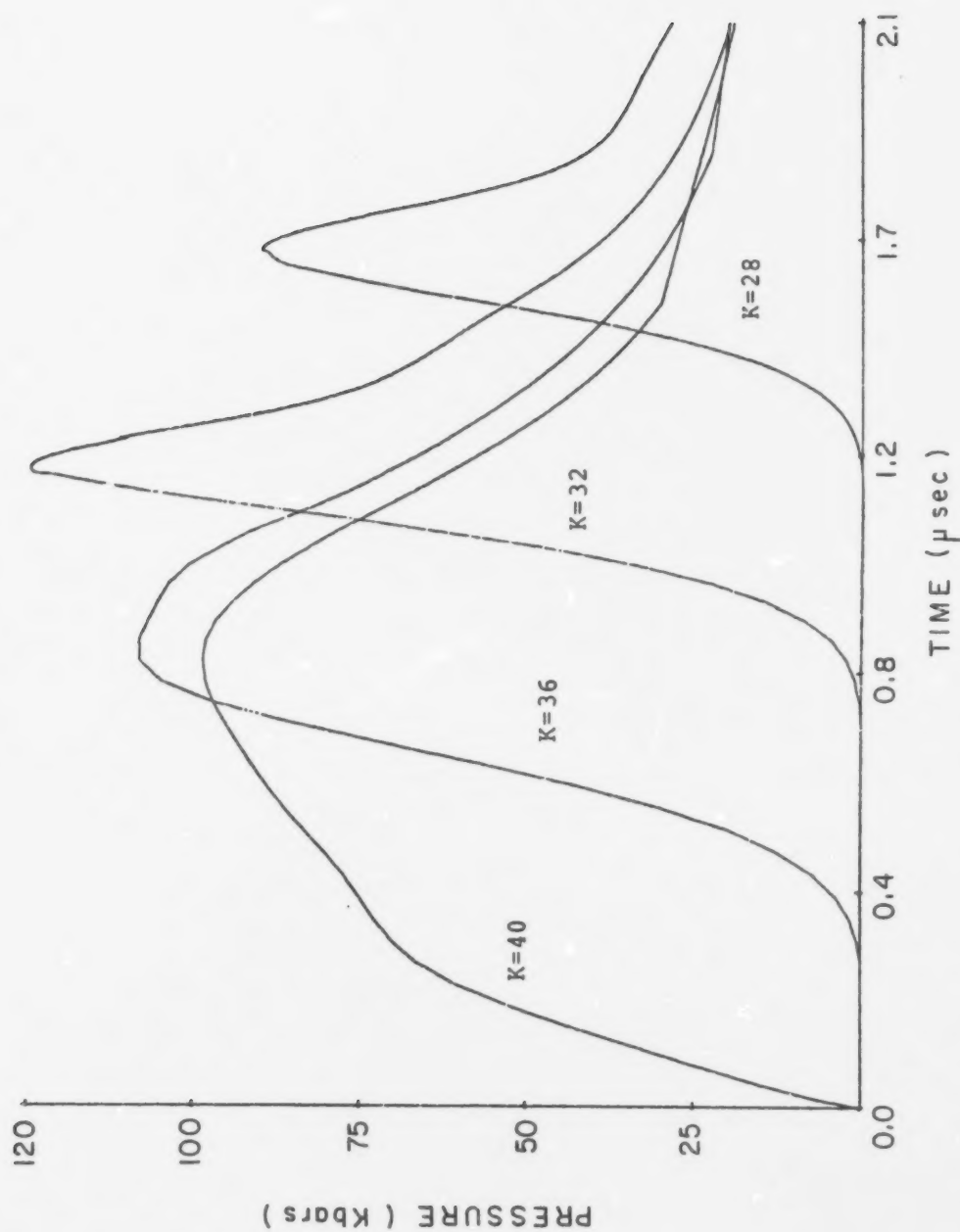


FIGURE 62: PRESSURE-TIME HISTORIES FOR COMPOSITION B IMPACTED BY A 10 MM DIAMETER STEEL PROJECTILE AT A VELOCITY OF 1200 m/sec.

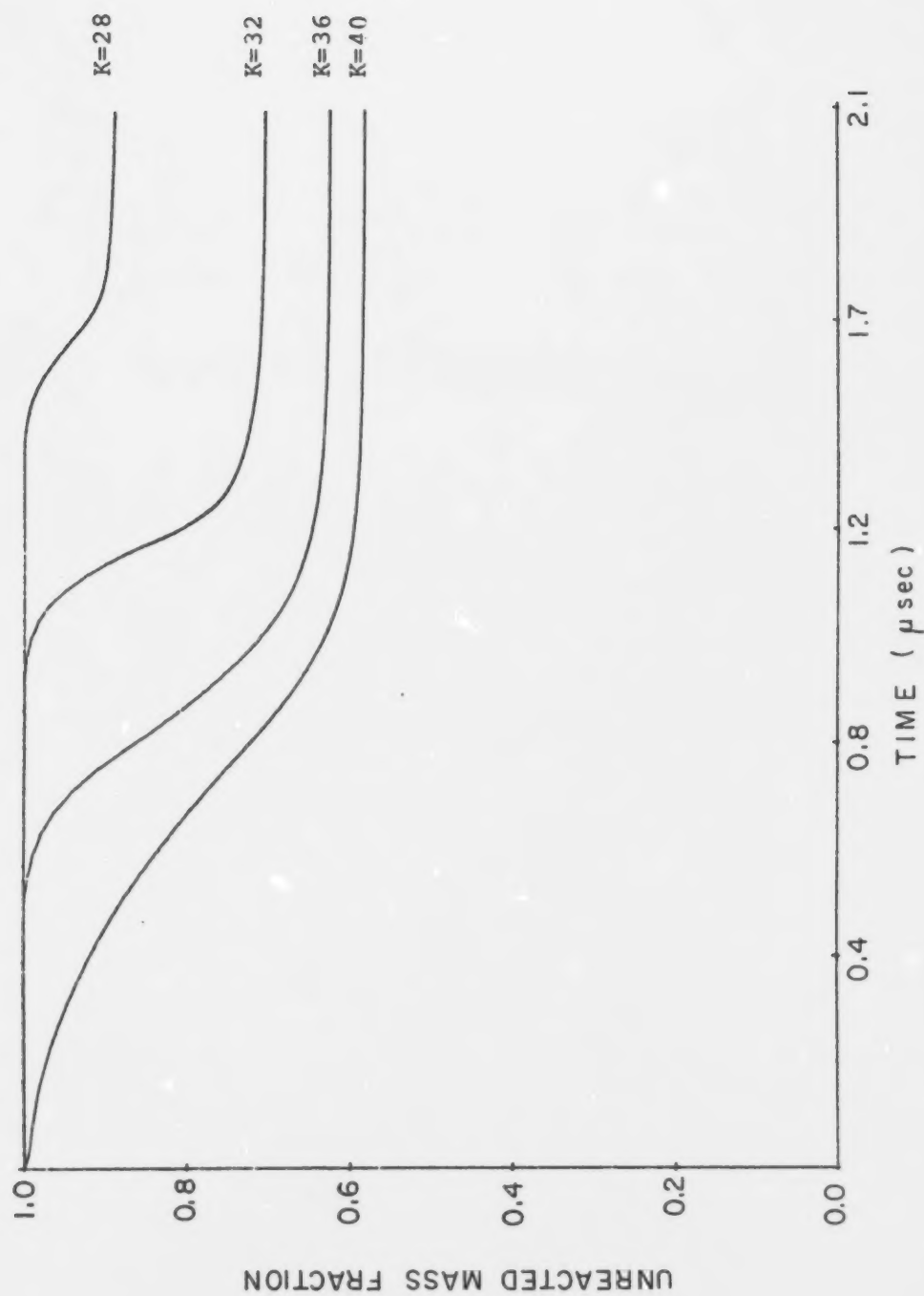


FIGURE 63 : UNREACTED EXPLOSIVE FRACTION-TIME FOR COMPOSITION B IMPACTED BY A 10 MM DIAMETER STEEL PROJECTILE AT A VELOCITY OF 1200 m/sec.

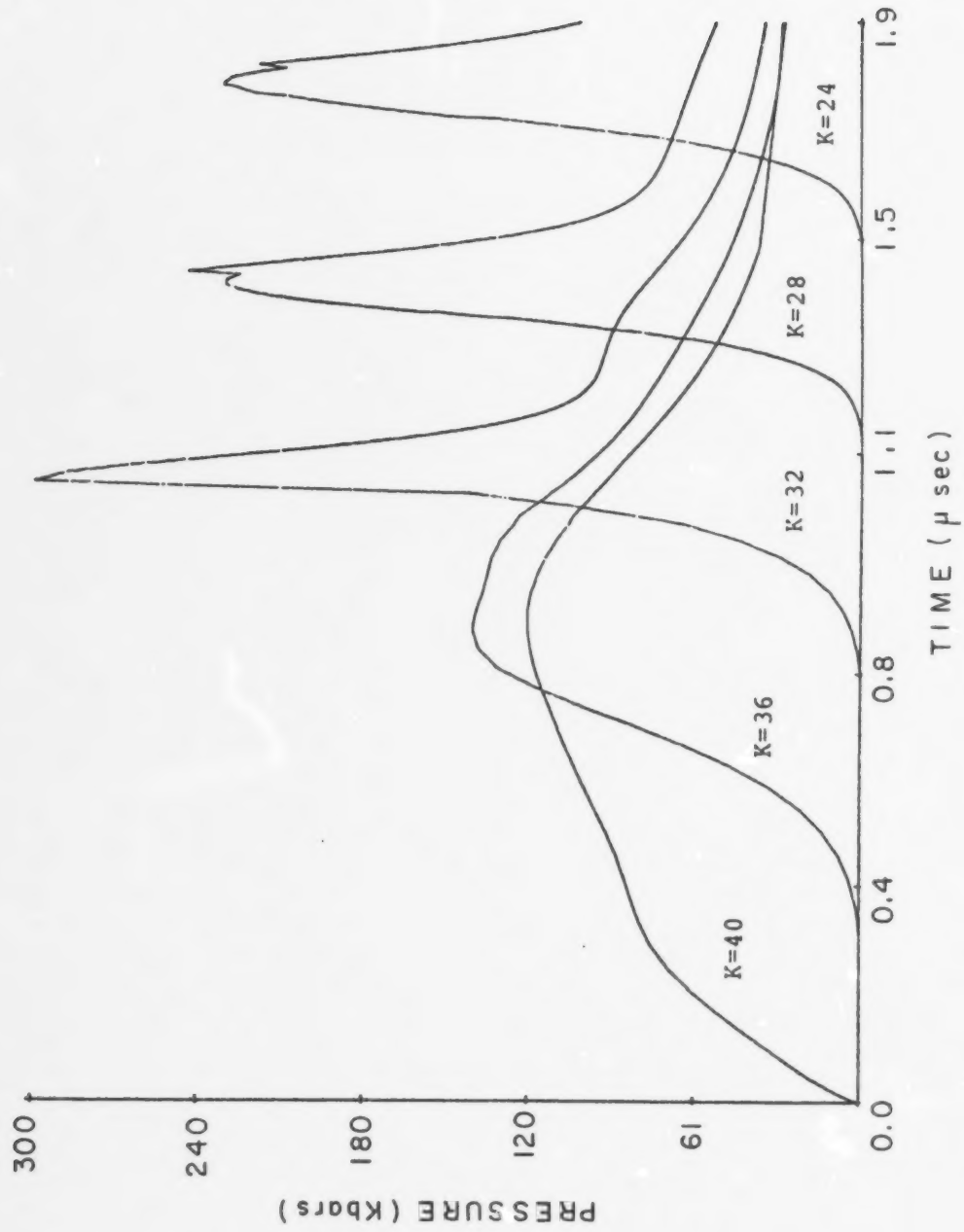


FIGURE 04 : PRESSURE-TIME HISTORIES FOR COMPOSITION B IMPACTED BY A 10 MM DIAMETER STEEL PROJECTILE AT A VELOCITY OF 1300 m/sec.

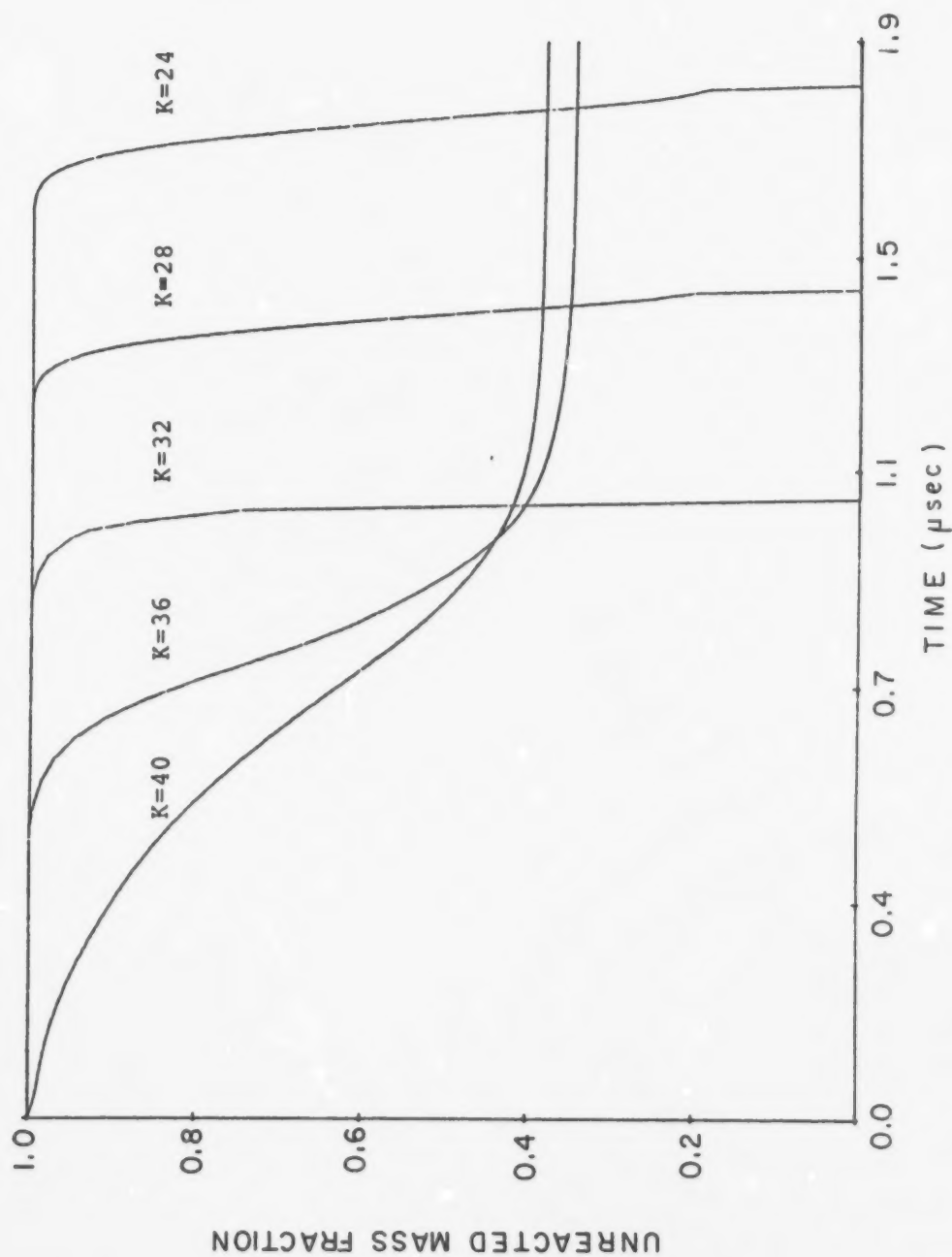


FIGURE 65: UNREACTED EXPLOSIVE FRACTION-TIME FOR COMPOSITION B IMPACTED BY A 10 MM DIAMETER STEEL PROJECTILE AT A VELOCITY OF 1,300 m/sec.

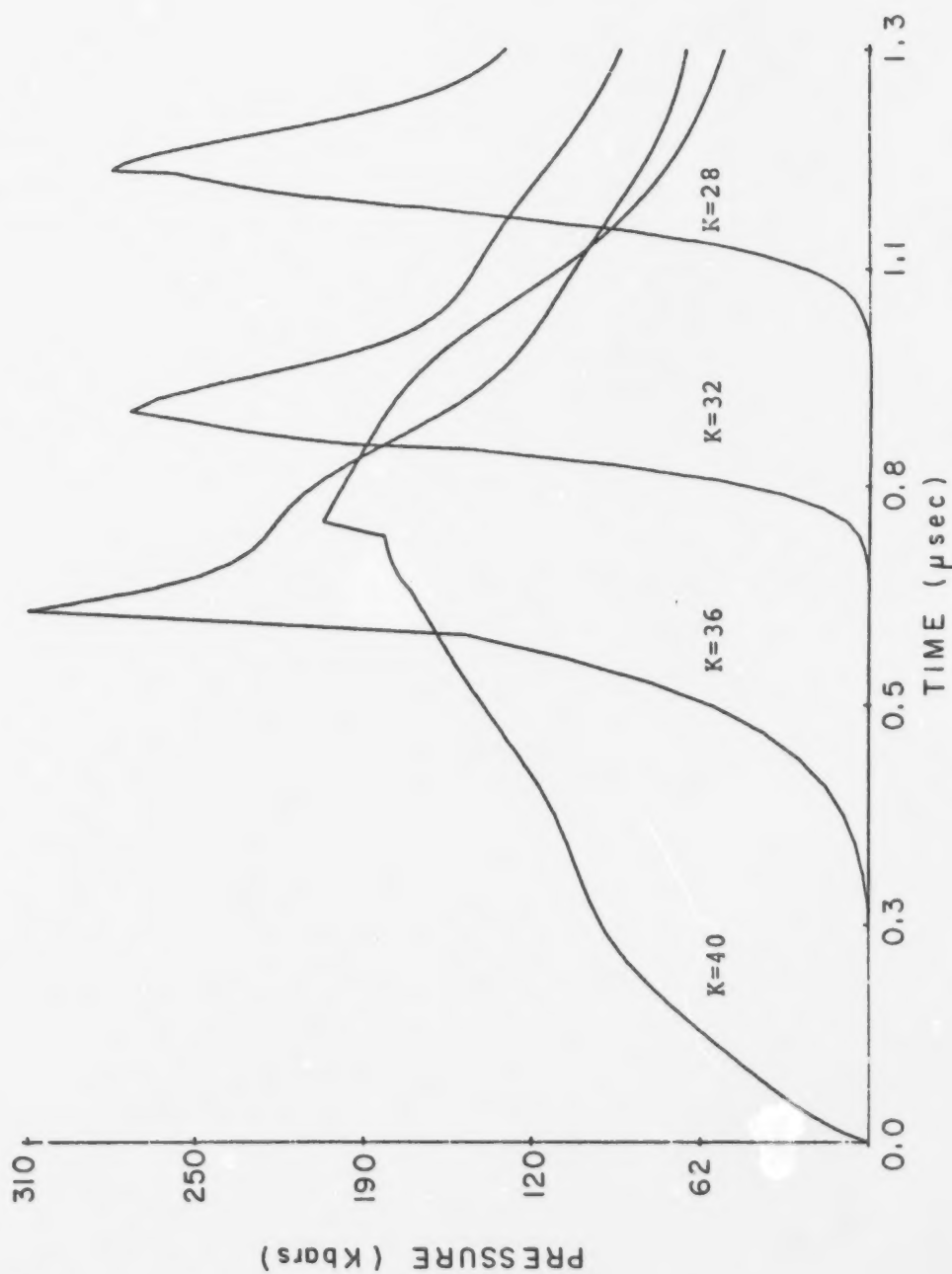


FIGURE 66: PRESSURE-TIME HISTORIES FOR COMPOSITION B IMPACTED BY A 10 MM DIAMETER STEEL PROJECTILE AT A VELOCITY OF 1500 m/sec.

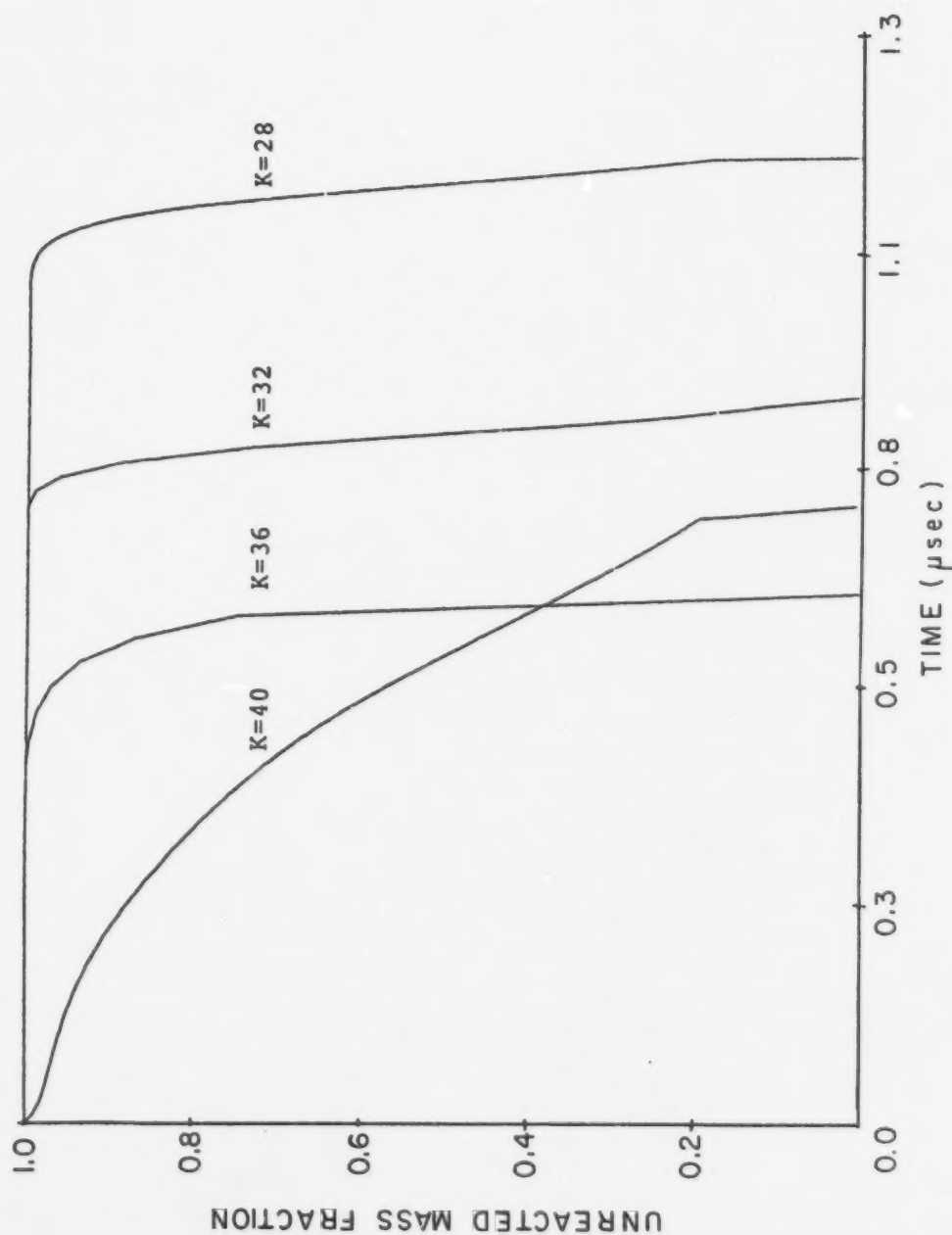


FIGURE 67; UNREACTED EXPLOSIVE FRACTION-TIME FOR COMPOSITION B IMPACTED BY A 10 MM DIAMETER STEEL PROJECTILE AT A VELOCITY OF 1500 m/sec.

and the impact velocity is high, initiation occurs almost immediately on impact. However if the projectile velocity is not high enough, detonation does not propagate but is quenched by the action of following rarefactions. This phenomenon is demonstrated in Figures 62 and 63.

#### ANFO

In the case of ANFO impact sensitivity data were calculated for impacts by aluminum flyer plates. The results are presented as pressure - time and fraction of unreacted material - time histories in Figures 68 to 73. The results compared with the experimental ones are shown in Table 7.9. The size of the grid was 1 mm x 1 mm.

The model was also tested against published projectile data for ANFO of density 0.95 g/cc. According to Johansson and Persson when the impactor is an aluminum projectile of 15 mm diameter and length the critical velocity to initiate ANFO is 1200 - 1230 m/s. The reactive hydrodynamic code "HYDREL" indicated detonation at a projectile velocity of 1200 m/s and failure at a velocity of 1000 m/s. Figures 74 to 77 present the calculated results.

#### Emulsion A

In the case of Emulsion A the impact of targets of the explosive by small brass projectiles was modelled. The projectiles had diameter and length of 13 mm. The results of the computer runs are presented as pressure - time and mass fraction of unreacted explosive time histories in Figures 78 to 83. The grid size in this case was 0.5 mm x 0.5 mm.



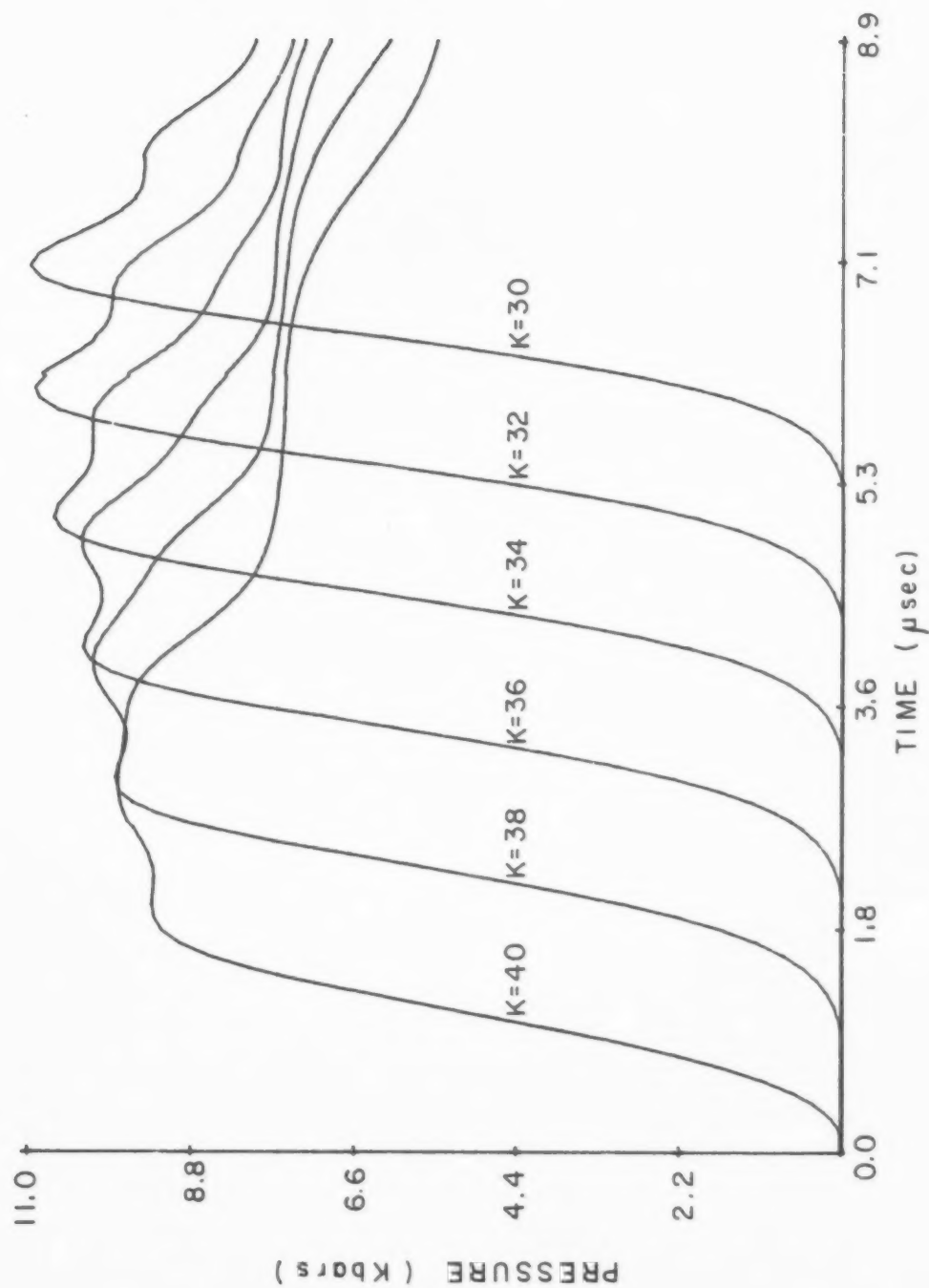


FIGURE 68: PRESSURE TIME HISTORIES FOR ANFO IMPACTED BY A 0.9 cm THICK ALUMINUM PLATE AT A VELOCITY OF 600 m/s

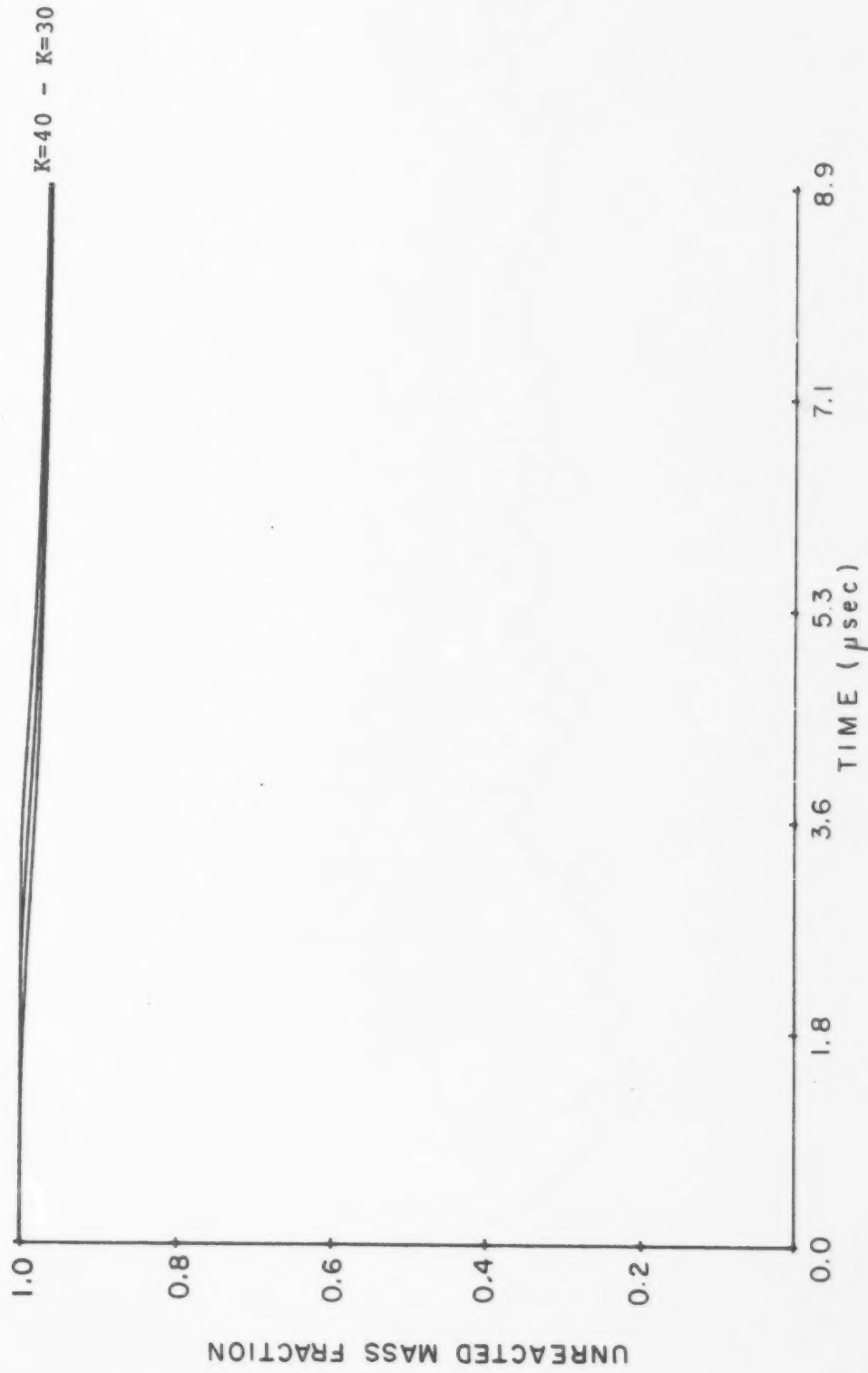


FIGURE 60: UNREACTED MASS FRACTION VS TIME FOR ANFO IMPACTED BY A 0.0 cm THICK ALUMINUM PLATE AT A VELOCITY OF 600 m/sec.

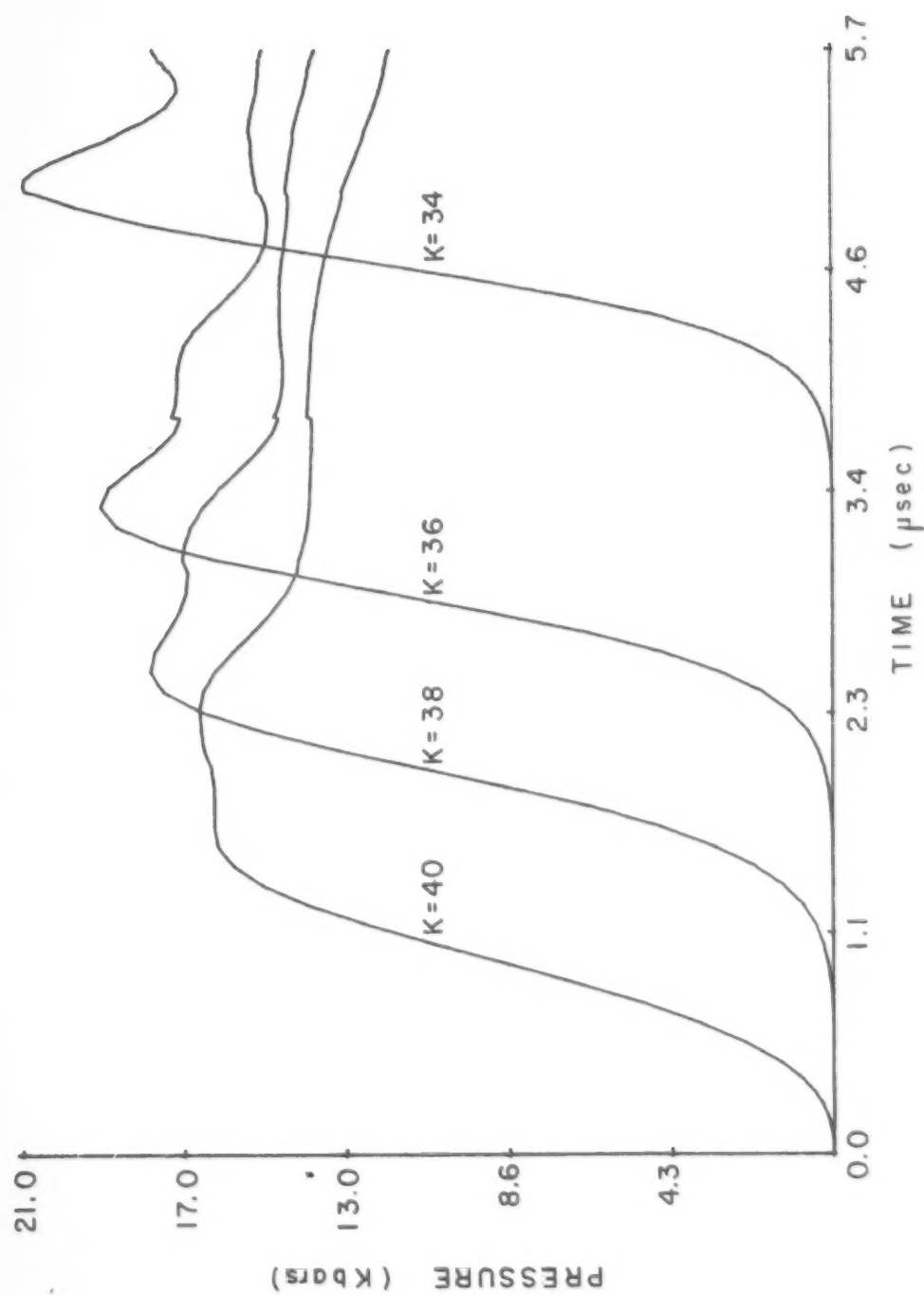


FIGURE 70 : PRESSURE TIME HISTORIES FOR ANO IMPACTED BY A 0.0 cm THICK ALUMINUM PLATE AT A VELOCITY OF 800 m/s

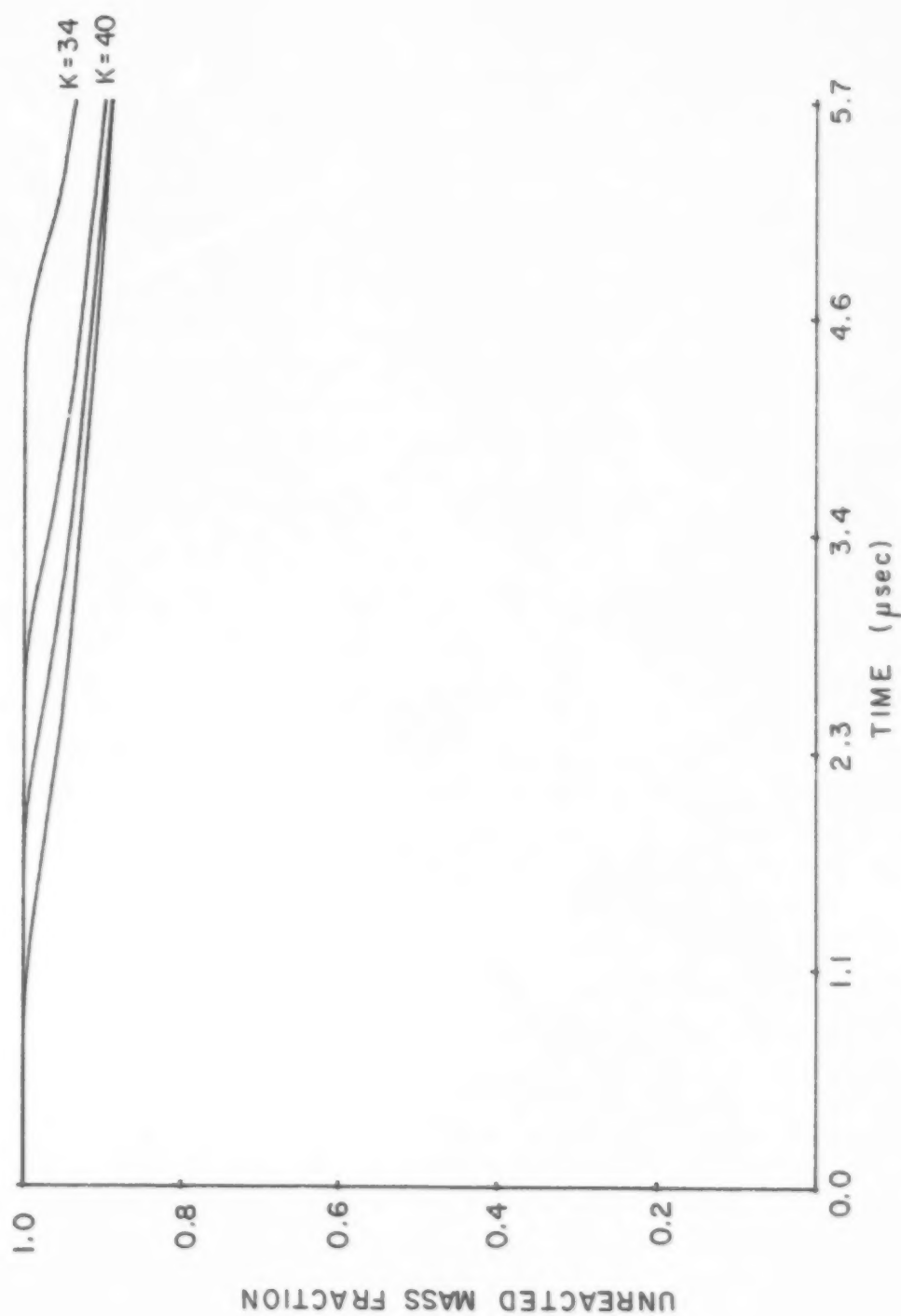


FIGURE 71 : UNREACTED MASS FRACTION VS TIME FOR ANFO IMPACTED BY A 0.9 cm THICK ALUMINUM PLATE AT A VELOCITY OF 800 m/s

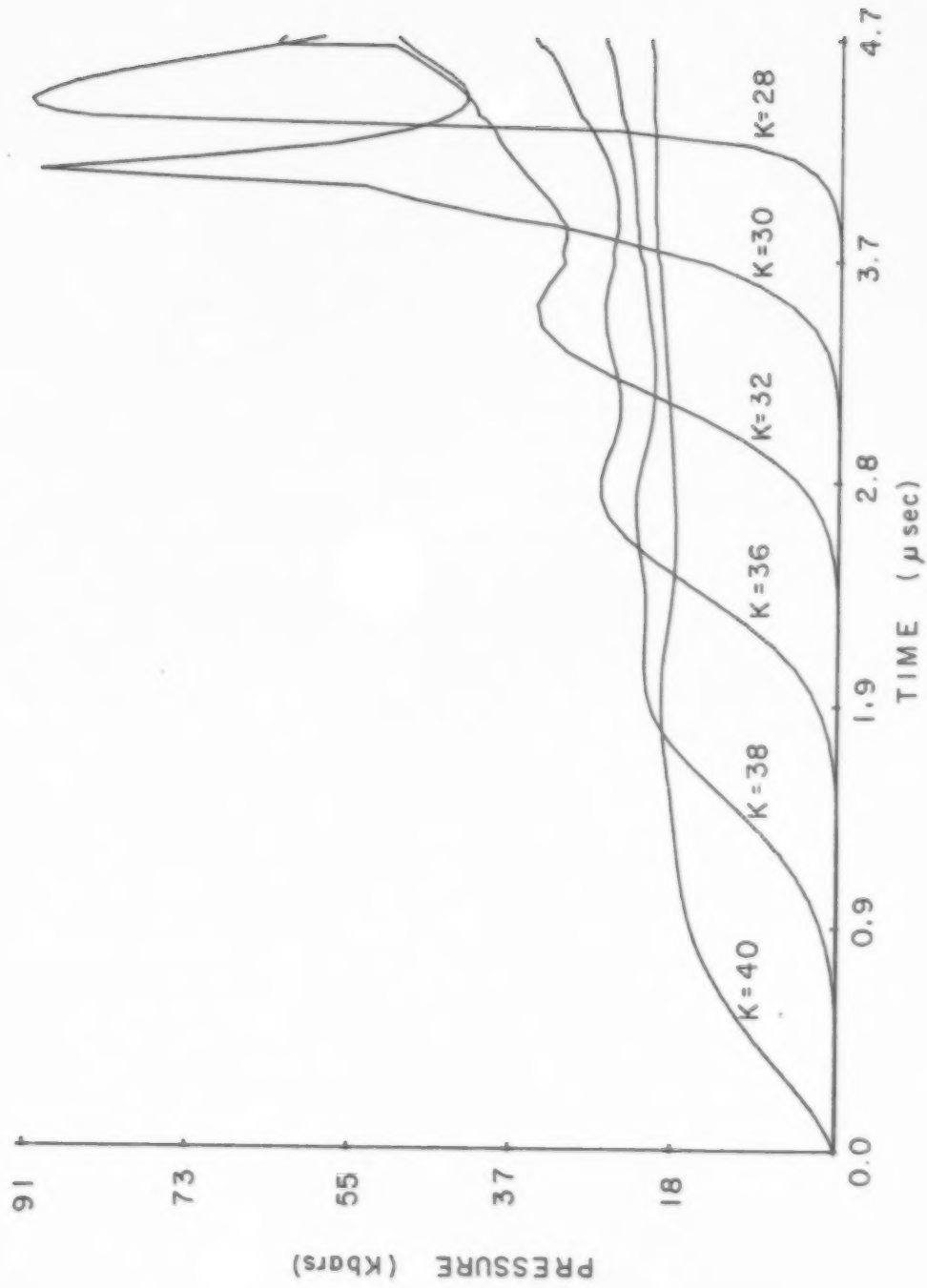


FIGURE 72: PRESSURE TIME HISTORIES FOR ANFO IMPACTED BY A 0.0 cm THICK ALUMINUM PLATE AT A VELOCITY OF 900 m/s

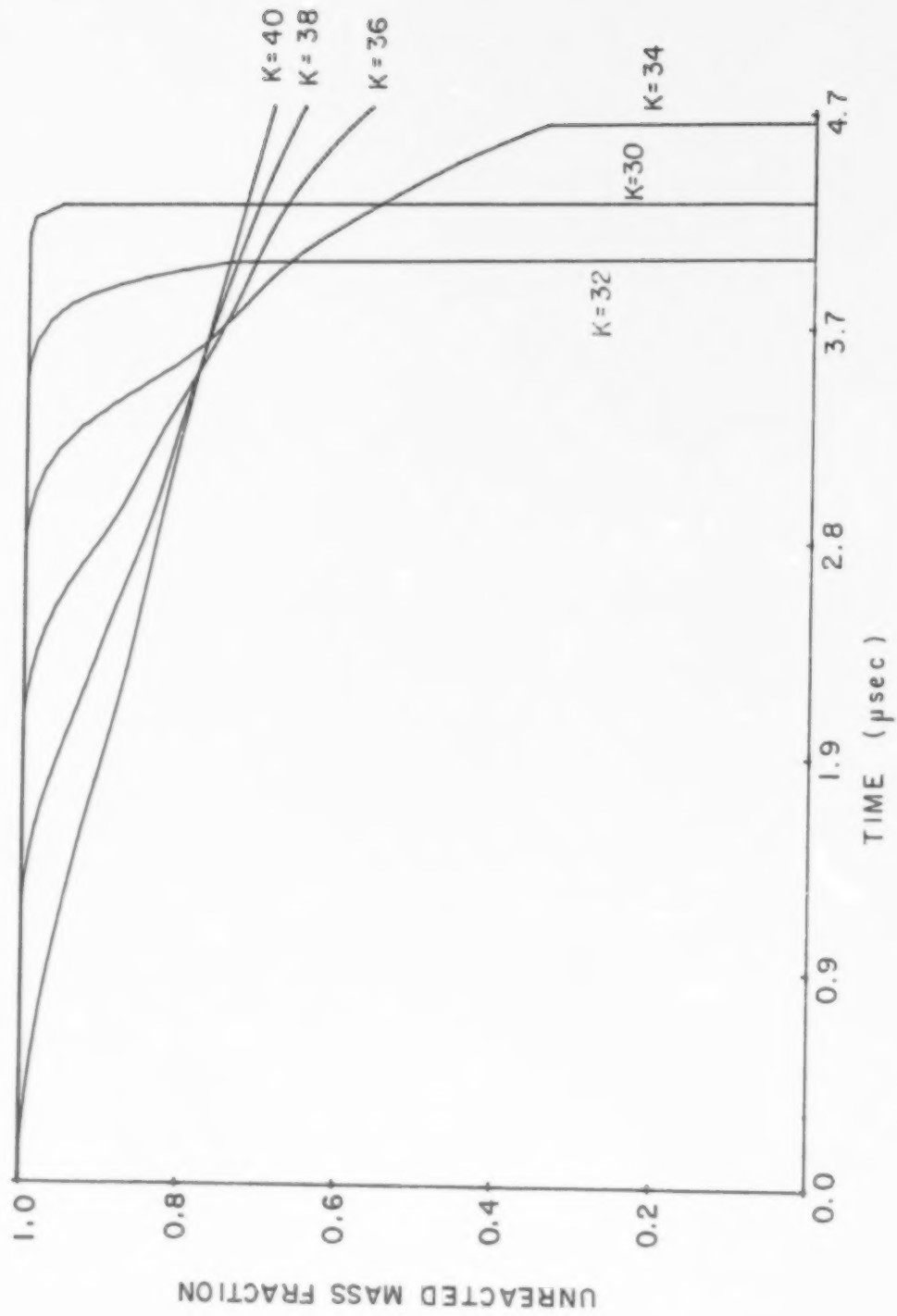


FIGURE 7.3 : UNREACTED MASS FRACTION VS TIME FOR ANFO IMPACTED BY A 0.9 cm THICK ALUMINUM PLATE AT A VELOCITY OF 900 m/s

TABLE 7.10: CALCULATED AND EXPERIMENTAL RESULTS FOR  
ANFO  $\rho = 0.95$  g/cc

| FLYER PLATE<br>THICKNESS<br>(cm) | EXPERIMENTAL<br>FAILURE VELOCITY<br>(m/s) | CALCULATED VELOCITY<br>(m/sec) and RESULTS   |
|----------------------------------|-------------------------------------------|----------------------------------------------|
| 0.95                             | 531 - 920                                 | 600 failure<br>800 marginal<br>900 detonated |

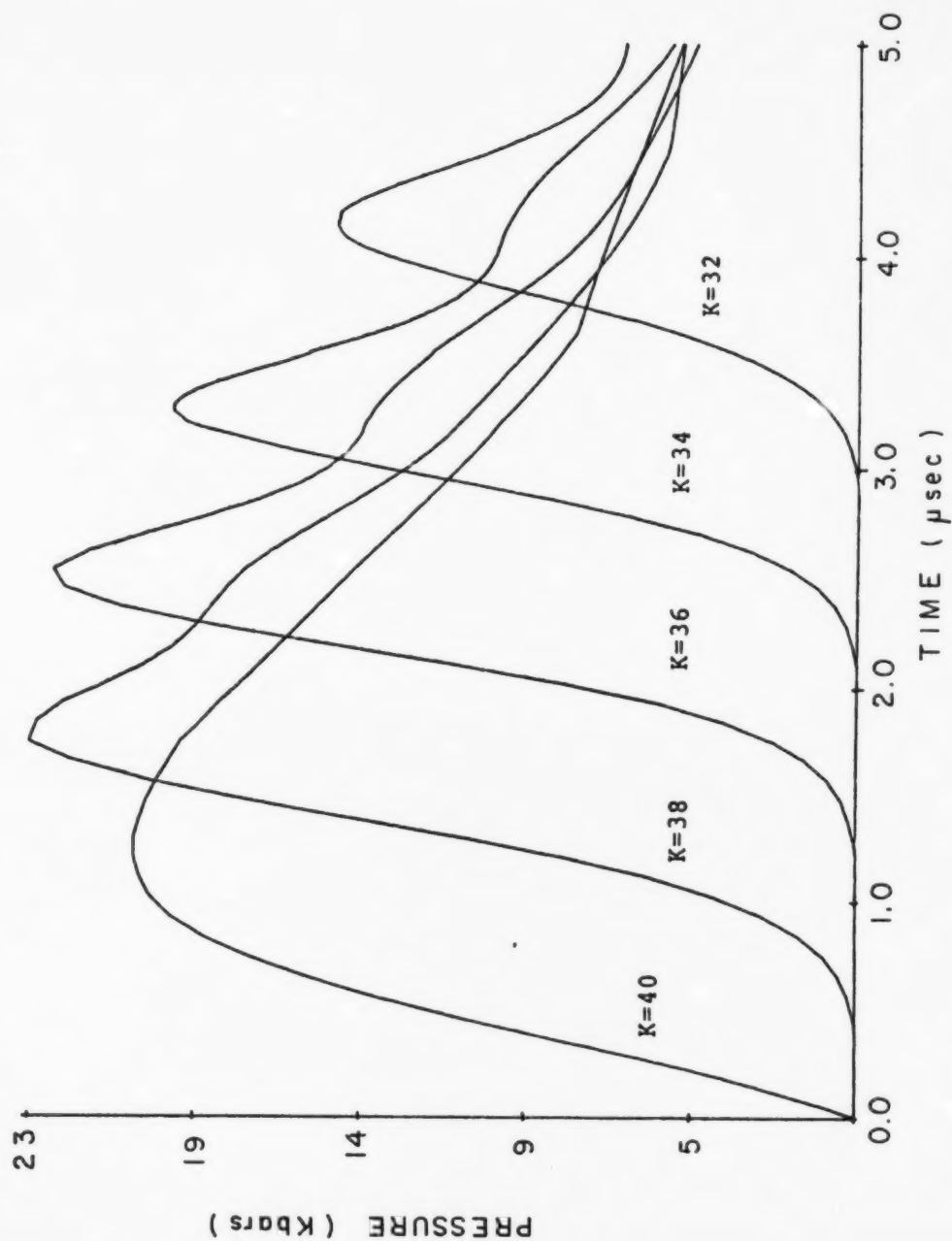


FIGURE 74 : PRESSURE-TIME HISTORIES FOR AN/FO IMPACTED BY A 15 MM DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF 1000 m/sec.



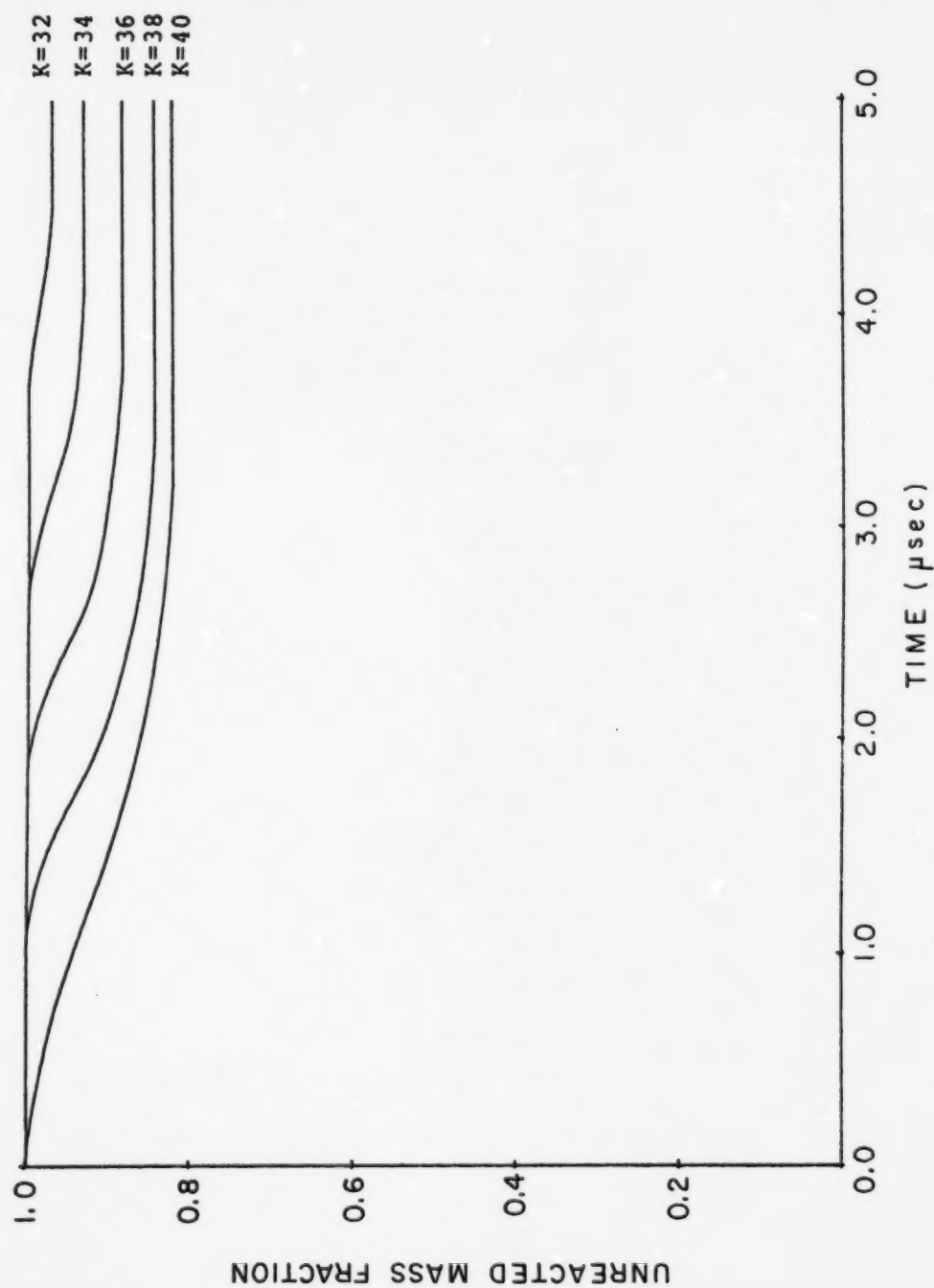


FIGURE 75: UNREACTED MASS FRACTION VS. TIME FOR AN/FO IMPACTED BY A 15 MM DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF 1000 m/sec.

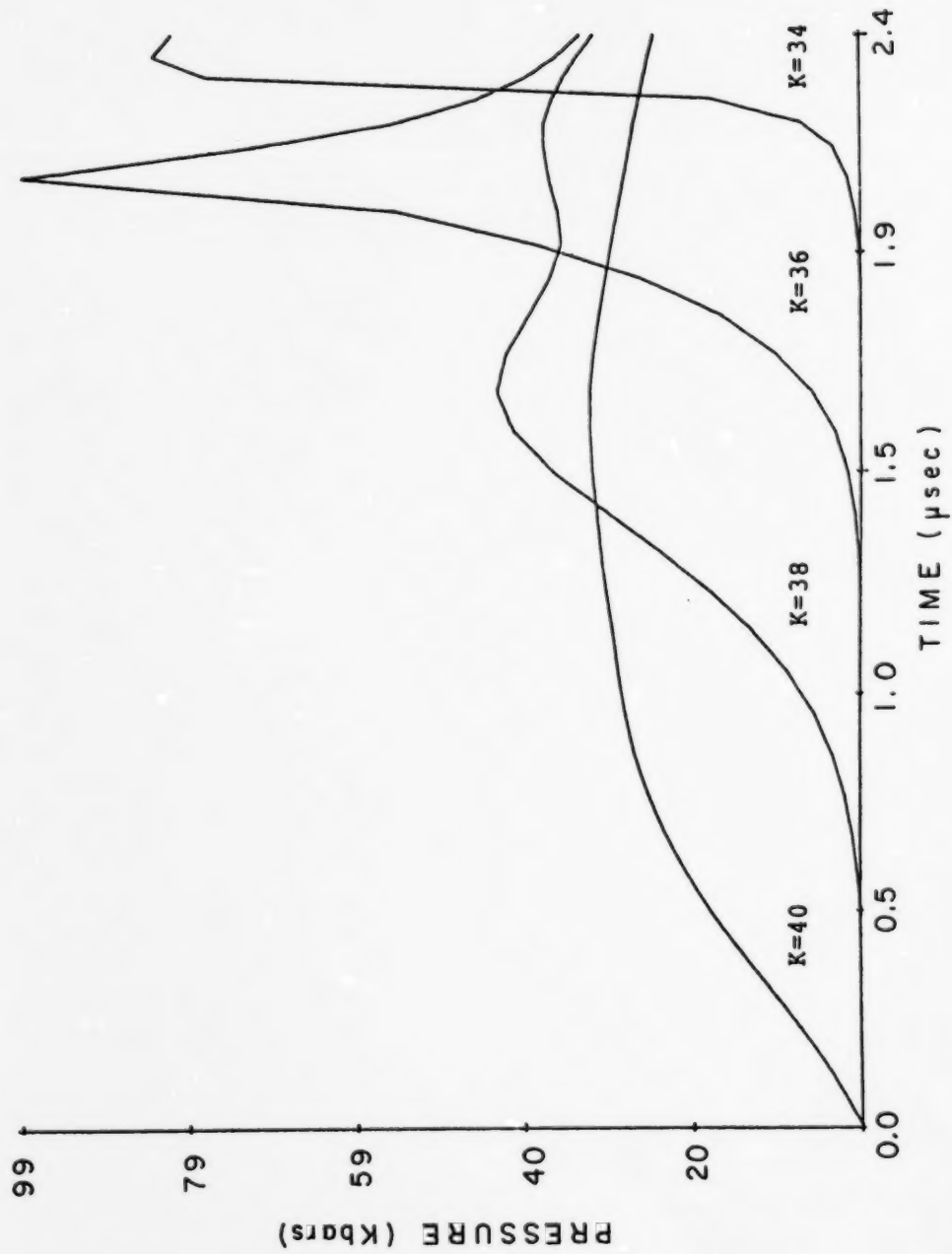


FIGURE 76: PRESSURE-TIME HISTORIES FOR AN/FO IMPACTED BY A 15 MM DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF 1200 m/sec.

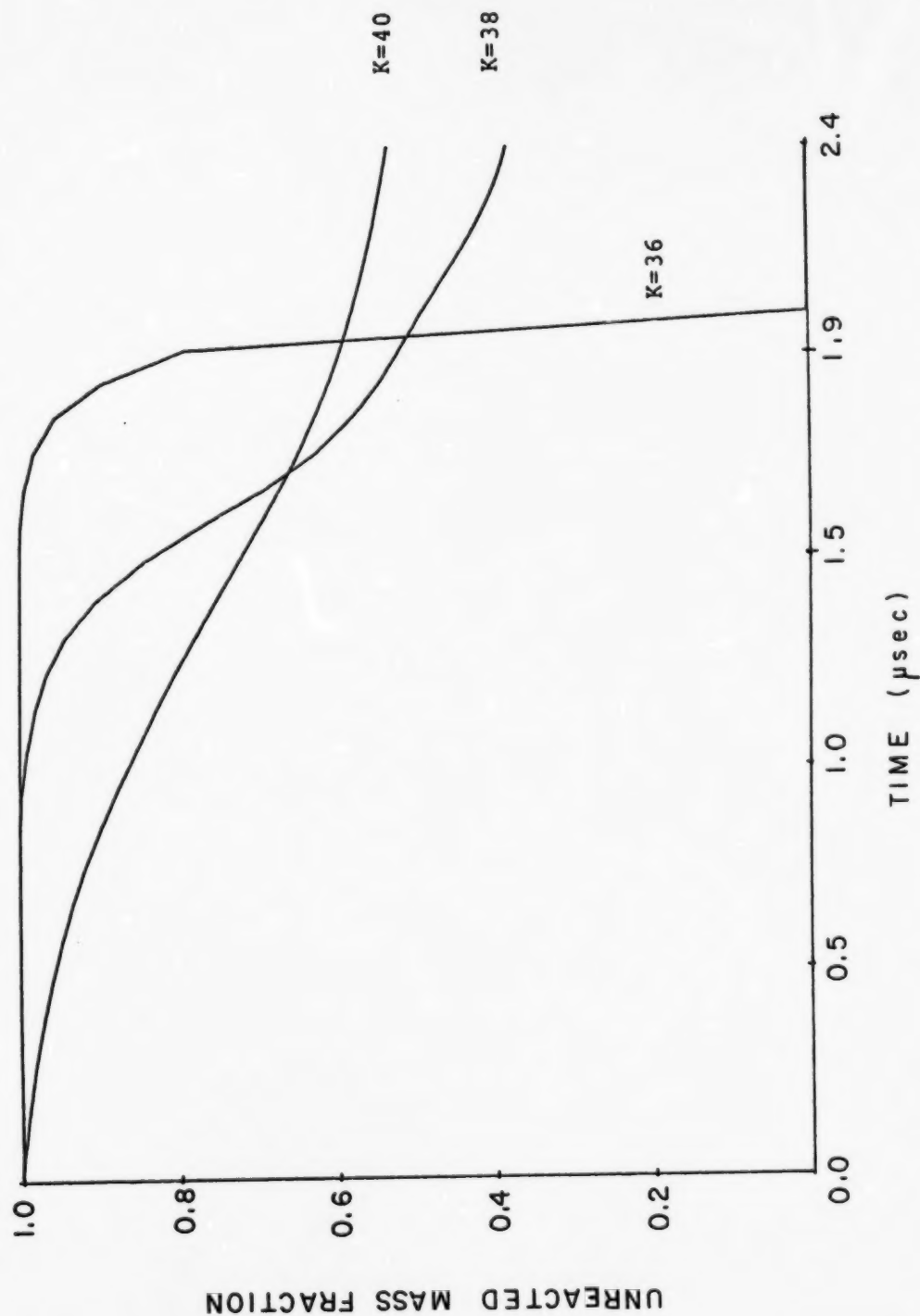


FIGURE 77 : UNREACTED MASS FRACTION VS. TIME FOR AN/FO IMPACTED BY A 15 MM DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF 1200 m/sec.

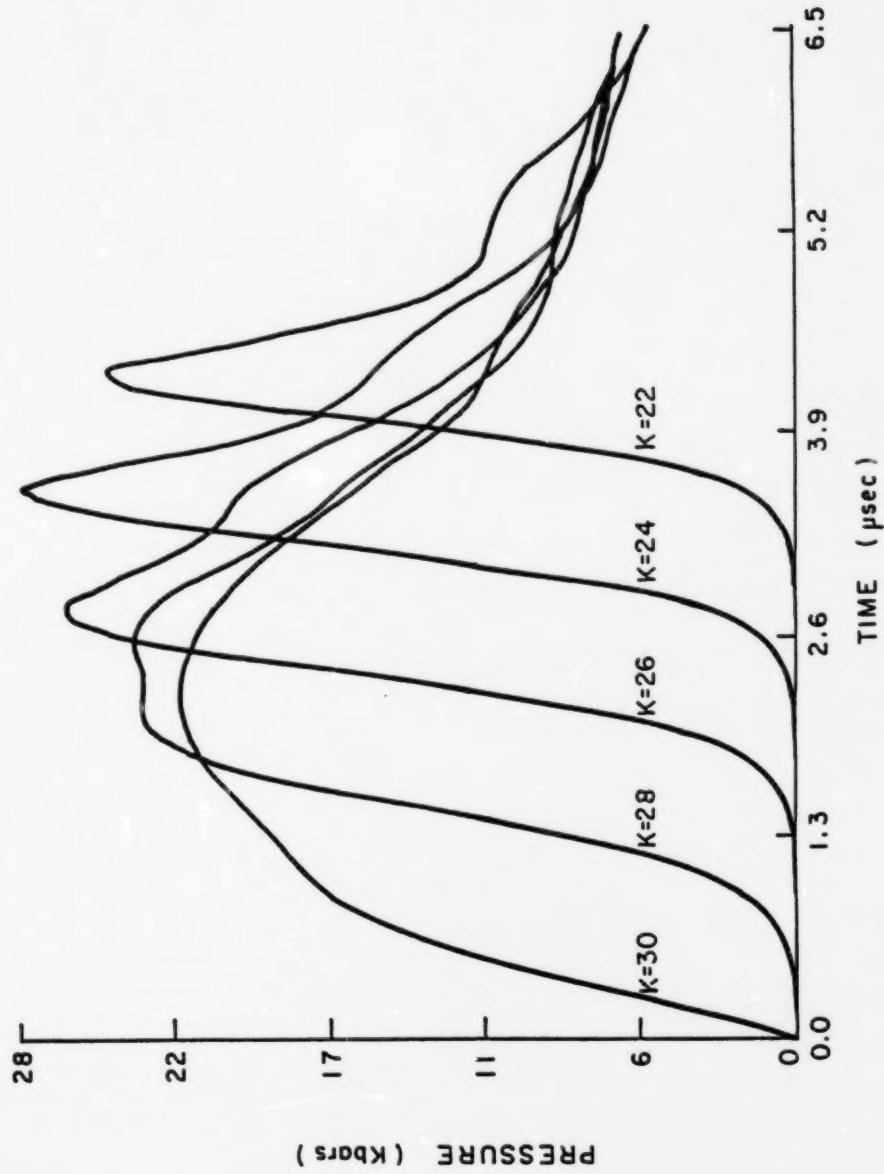


FIGURE 78: PRESSURE TIME HISTORIES FOR EMULSION A IMPACTED BY A 1.3mm DIAMETER BRASS PROJECTILE OF A VELOCITY OF 700 m/s

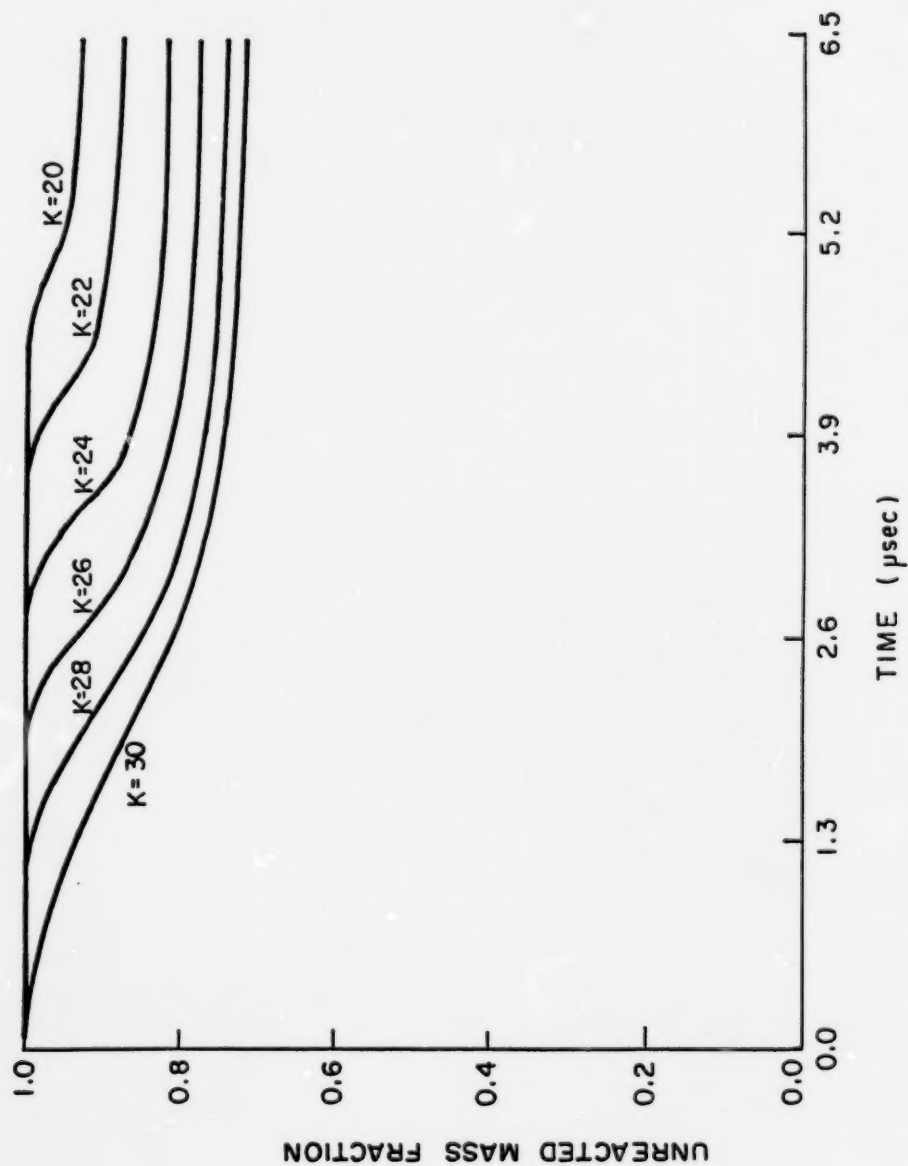


FIGURE 79 : MASS FRACTION OF UNREACTED EXPLOSIVE VERSUS TIME EMULSION A  
IMPACTED BY A 1.3mm DIAMETER BRASS PROJECTILE AT A VELOCITY OF 700 m/s

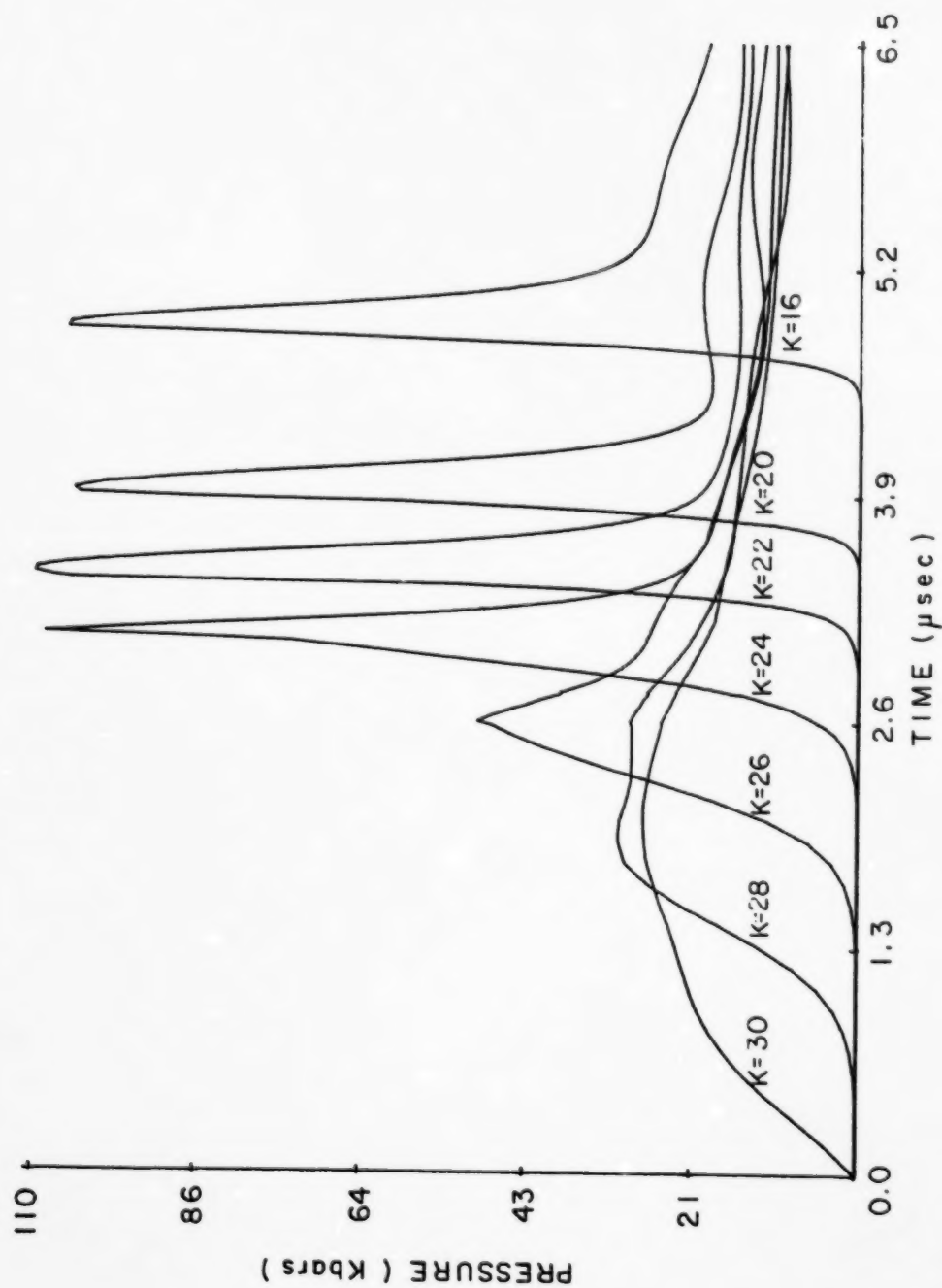


FIGURE 8Q PRESSURE TIME HISTORIES FOR ENULSION A IMPACTED BY A 1.3mm BRASS PROJECTILE AT A VELOCITY OF 750 m/sec

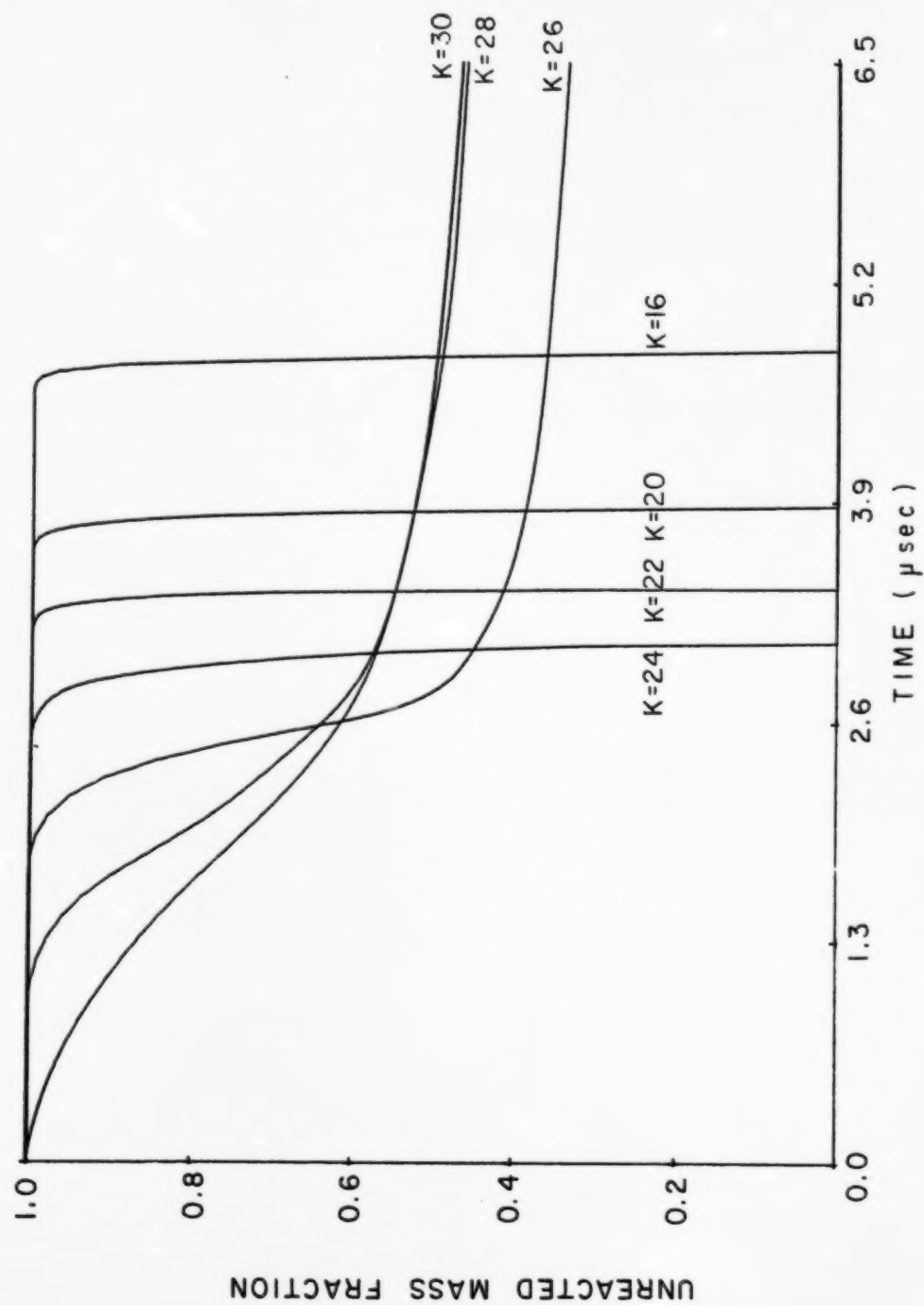


FIGURE 51 : MASS FRACTION OF UNREACTED EXPLOSIVE TIME HISTORIES FOR EMULSIONS IMPACTED BY A 1.2mm DIAMETER BRASS PROJECTILE AT A VELOCITY OF 750 m/sec

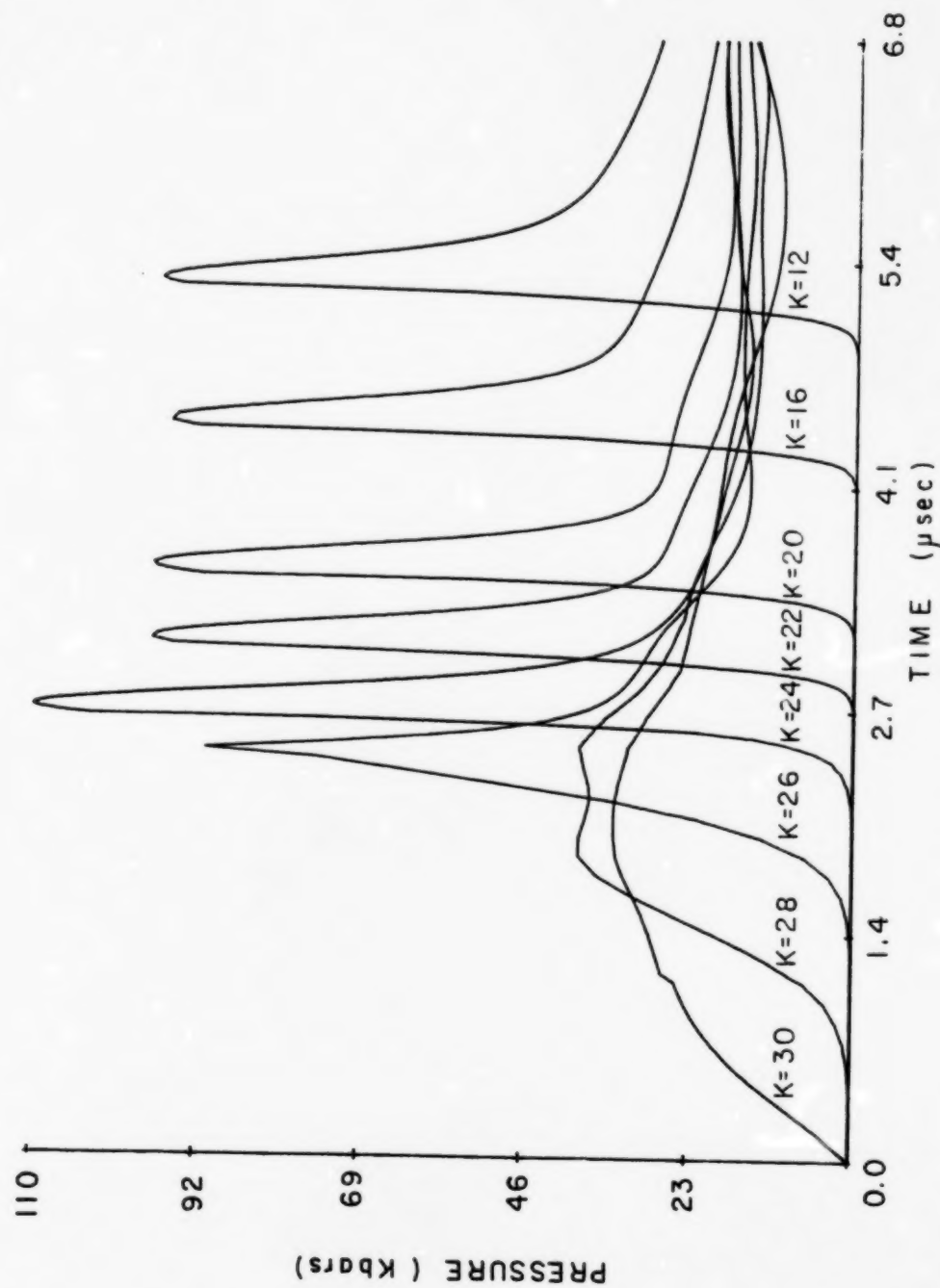


FIGURE S2: PRESSURE TIME HISTORIES FOR EROSION OF A 1.3mm DIAMETER BRASS PROJECTILE AT A VELOCITY OF 500 m/sec



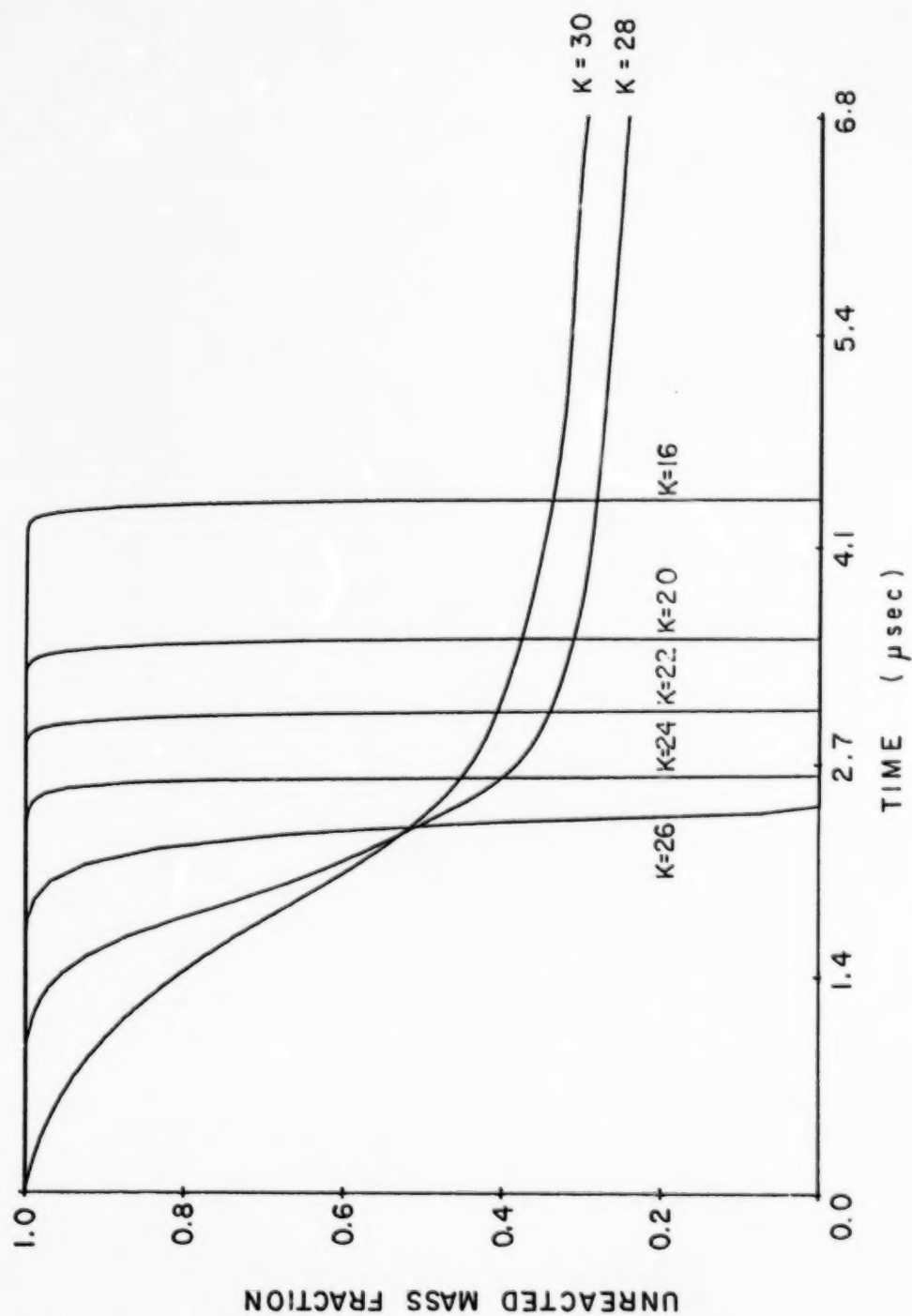


FIGURE 8.3: UNREACTED MASS FRACTION - TIME HISTORIES FOR ER/L503 A IMPACTED BY A 1.3 mm DIAMETER BRASS PROJECTILE AT A VELOCITY OF 800 m/sec.

The results are also summarized in Table 7.11. In order to demonstrate the influence of the material of the impactor some results were calculated for the case of aluminum impactor projectiles. The results are shown in Figures 84 to 87. It follows that the critical velocity of the projectile has to be increased to 850 - 900 m/sec in order to initiate the emulsion. This is consistent with experimental observations regarding aluminum and brass projectiles.

#### Emulsion B

The impact of Emulsion B targets by small brass projectiles was modelled. The projectiles were 13 mm in diameter and length. The results of the calculations are presented as pressure - time and mass fraction of unreacted explosive - time histories in Figures 88 to 91.

The results are also summarized in Table 7.12 where they are compared against the experimental ones.

#### Emulsion C

The impact of the cap insensitive Emulsion C by small brass projectiles and aluminum flyer plates was modelled. The results of the calculations are shown in Figures 91 to 98. The element size of the grid was 0.5 mm x 0.5 mm. The results are also summarized and compared against the experimental ones in Table 7.13.

TABLE 7.11: CALCULATED AND EXPERIMENTAL RESULTS FOR EMULSION A

| PROJECTILE<br>DIAMETER       | EXPERIMENTAL<br>FAILURE VELOCITY | CALCULATED VELOCITY<br>(m/sec) and RESULTS      |
|------------------------------|----------------------------------|-------------------------------------------------|
| 13 mm<br>brass projectile    | 711 - 745                        | 700 failure<br>750 detonation<br>800 detonation |
| 13 mm<br>aluminum projectile | -                                | 850 failure<br>900 detonation                   |

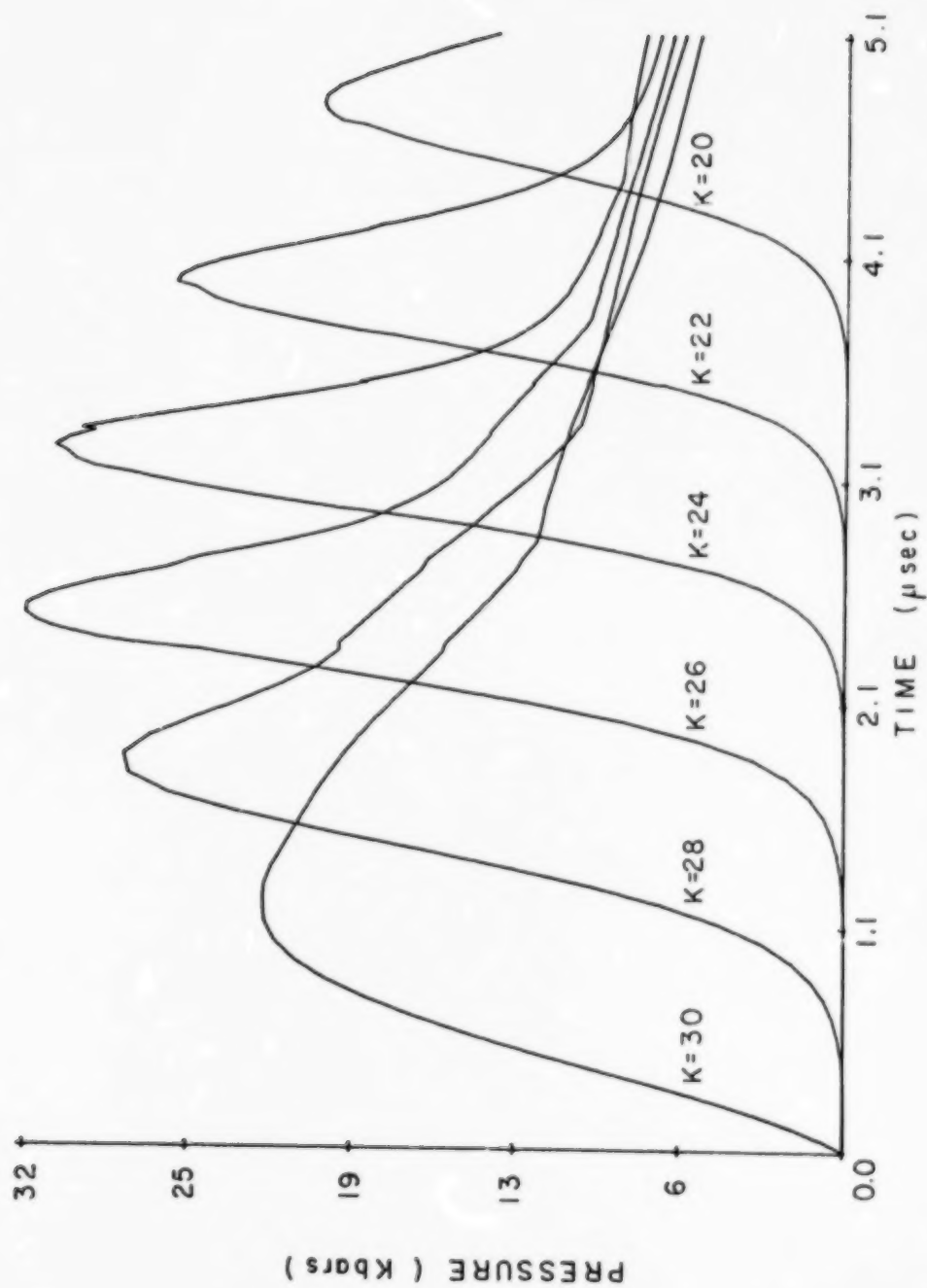


FIGURE 54 : PRESSURE-TIME HISTORIES FOR CURLS ON A IMPACTED BY A 1.3 mm ALUMINUM PROJECTILE AT A VELOCITY OF 550 m/sec.

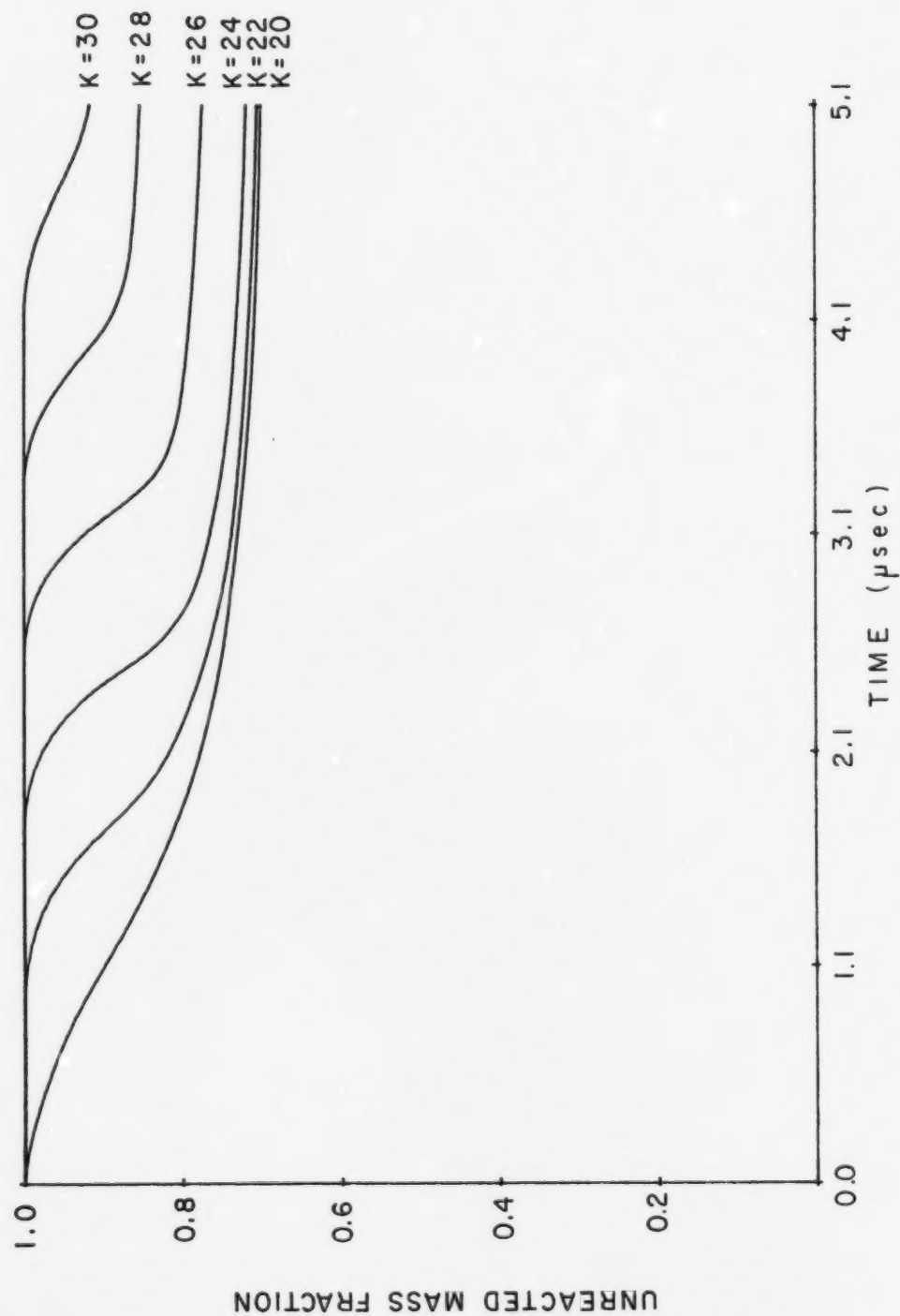


FIGURE 85 : MASS FRACTION OF UNREACTED EXPLOSIVE VS. TIME FOR EMULSION A IMPACTED BY A 1.5 mm DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF 550 m/sec.

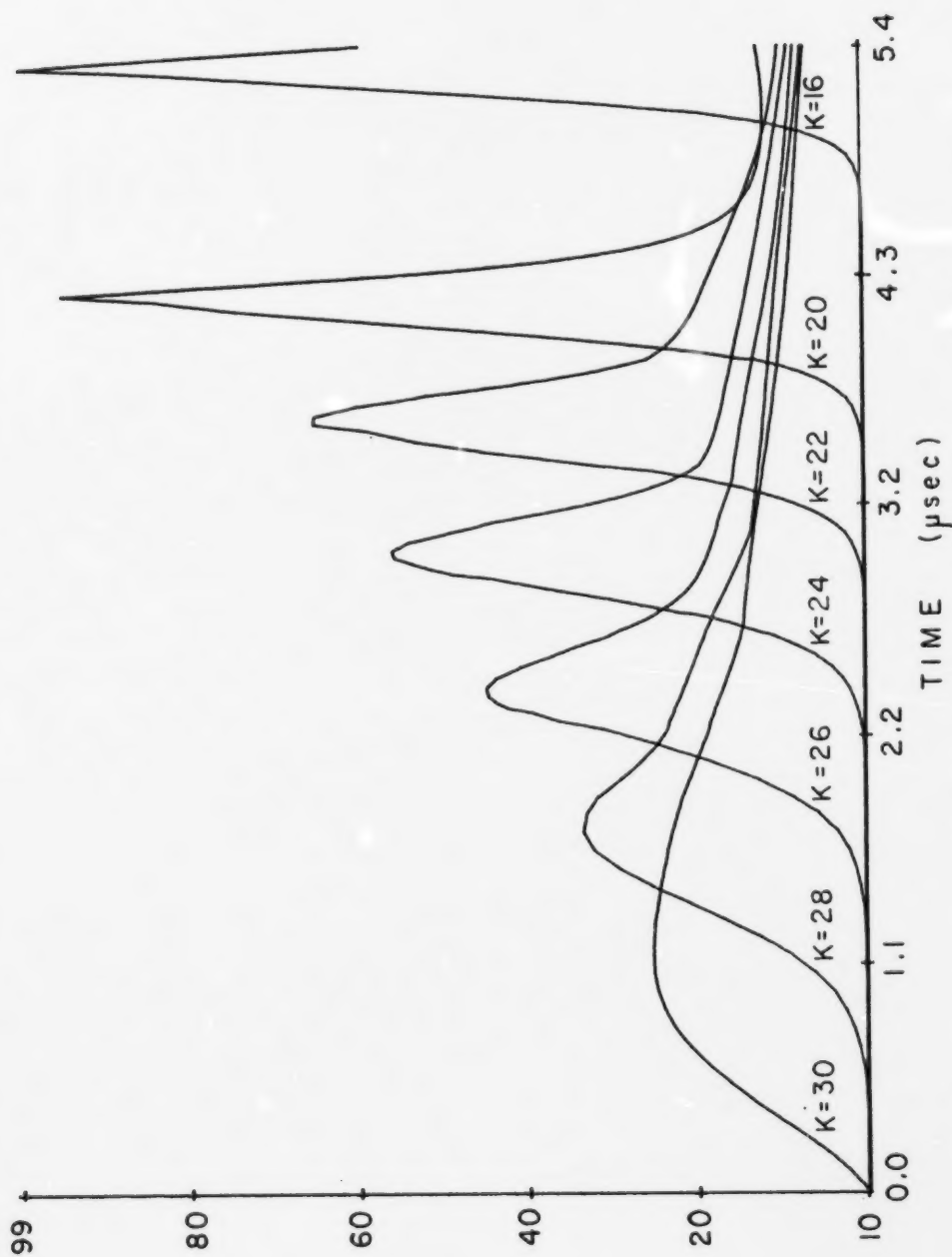


FIGURE 86: PRESSURE-TIME HISTORIES FOR EMULSION A IMPACTED BY A 13 mm DIAMETER ALUMINUM PROJECTILE OF A VELOCITY OF 900 m/sec.

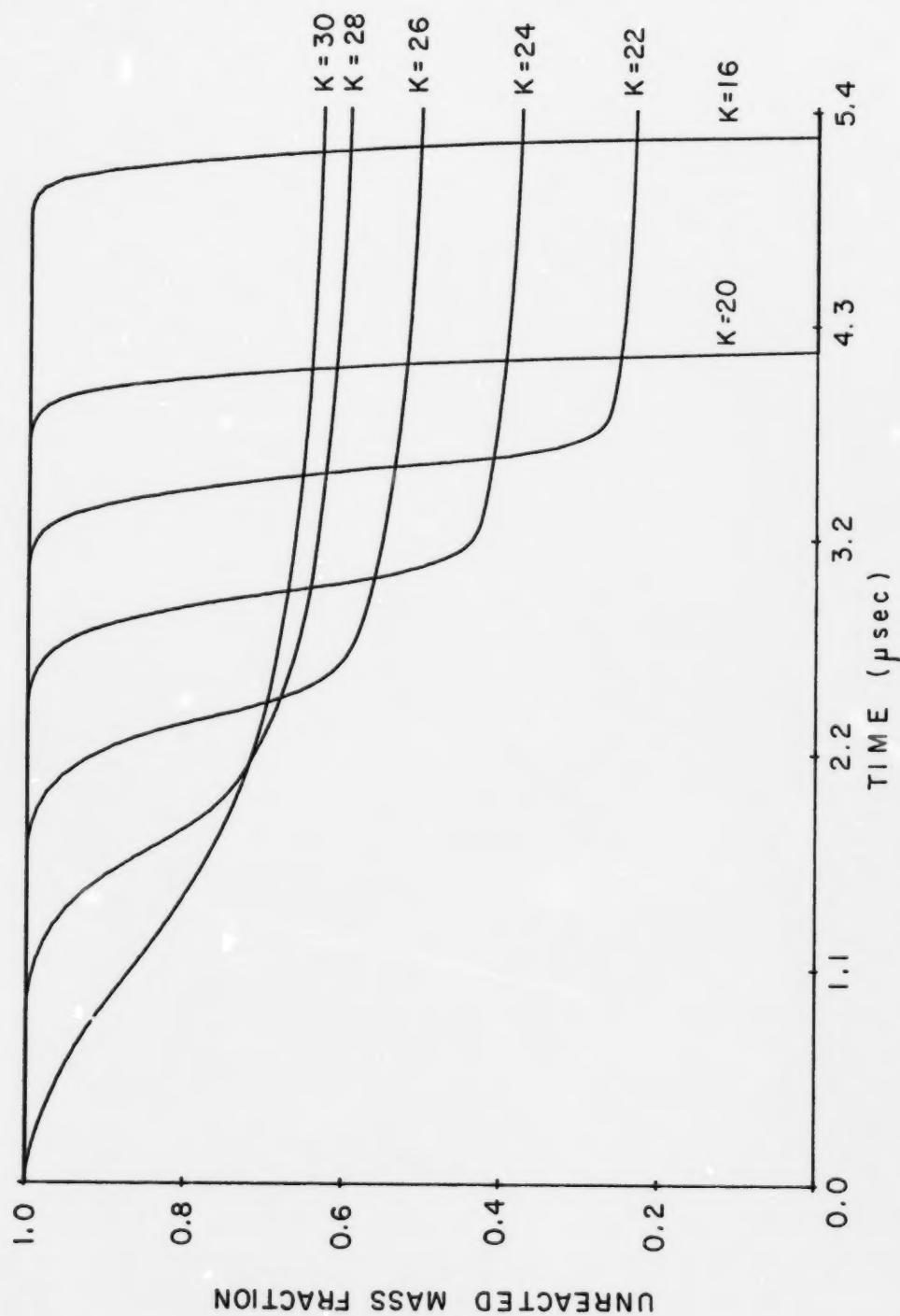


FIGURE 87: MASS FRACTION OF UNREACTED EXPLOSIVE VS. TIME FOR EMULSION A IMPACTED BY A 1.3 mm DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF 900 m/sec.

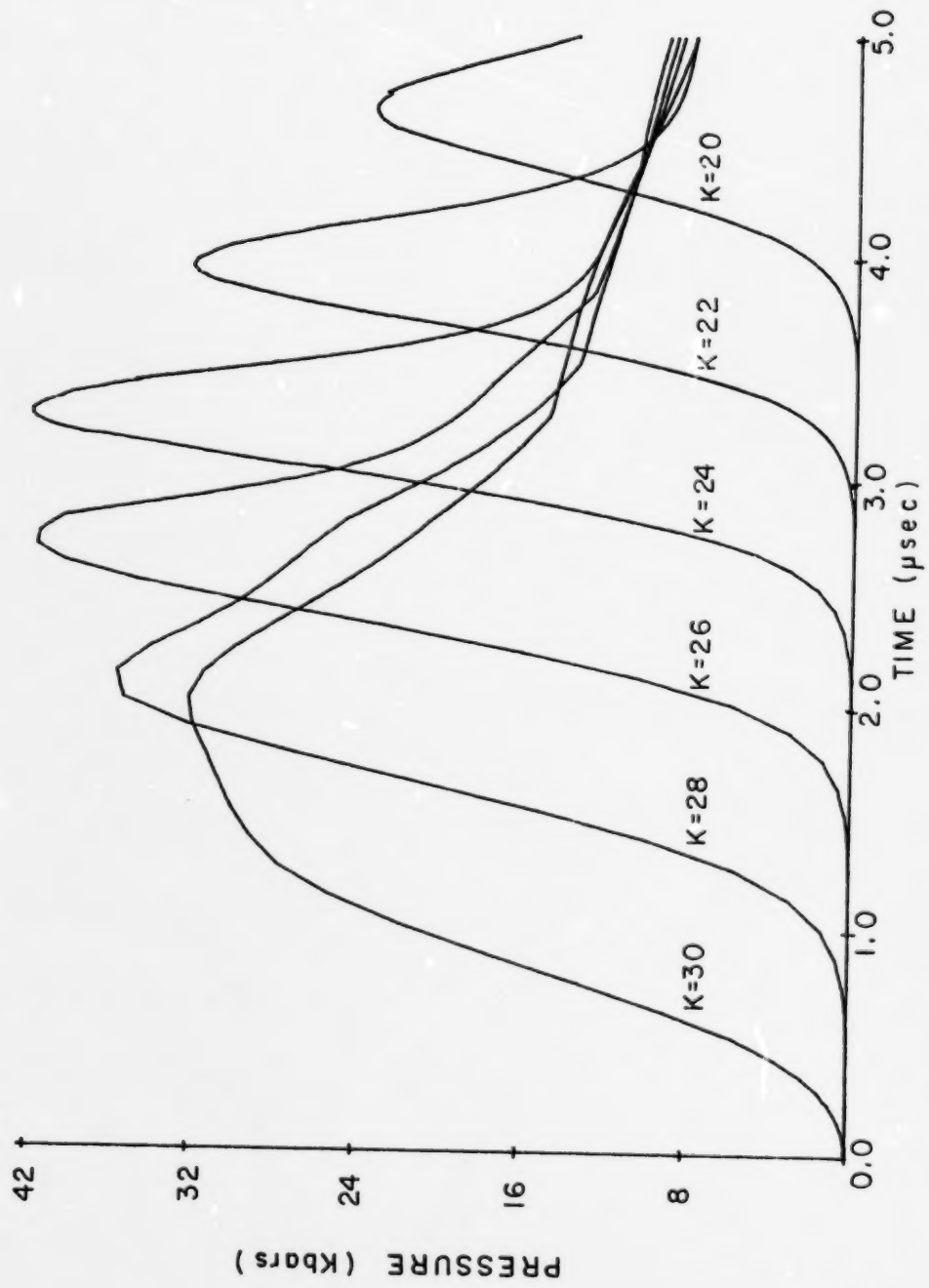


FIGURE 88: PRESSURE-TIME HISTORIES FOR "EQUIL" ON 3 "IMPACTED BY A 1.3 mm DIAMETER BRASS PROJECTILE AT A VELOCITY OF 850 m/sec.



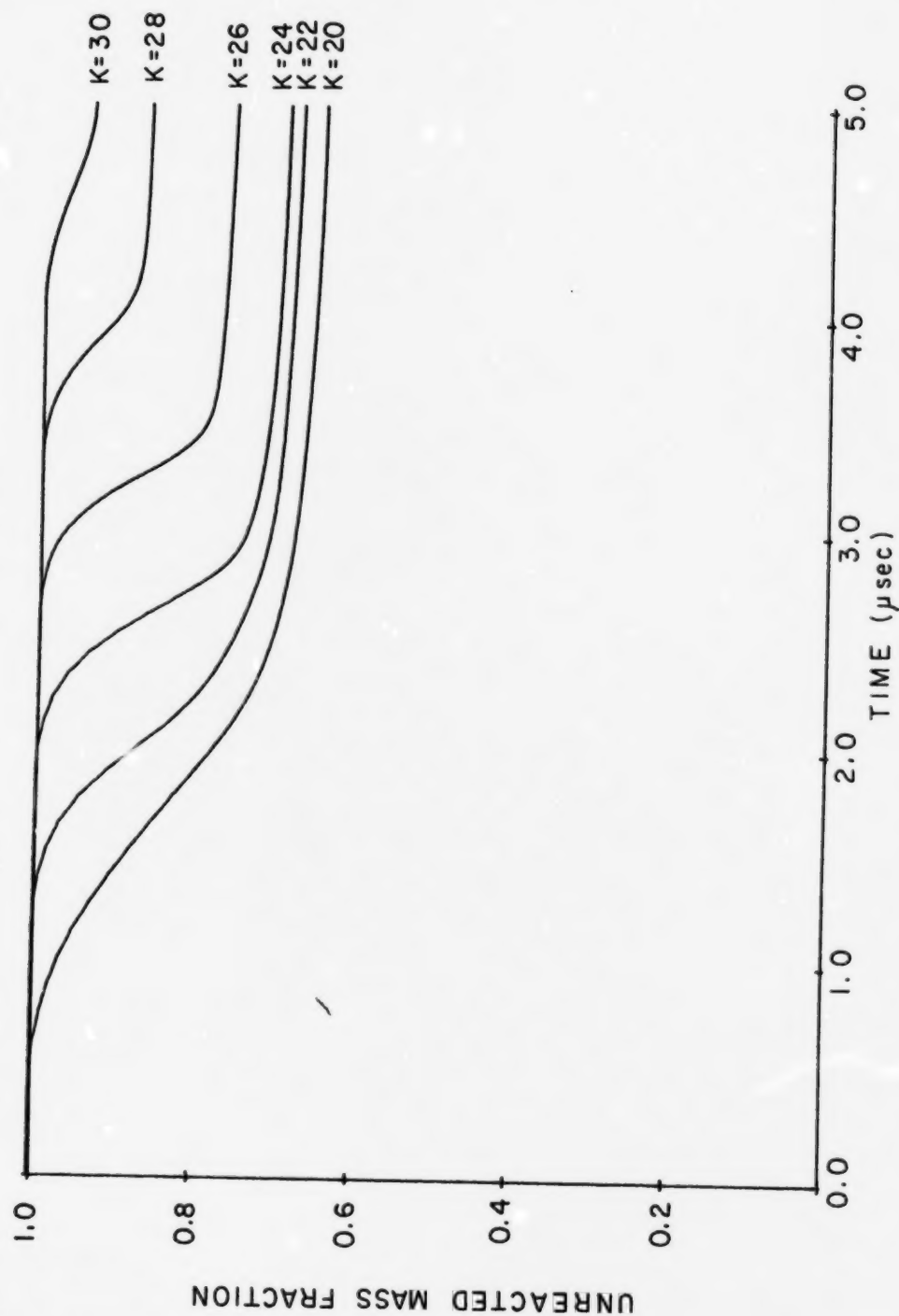


FIGURE 80: MASS FRACTION OF UNREACTED EXPLOSIVE VERSUS TIME FOR EMULSION B IMPACTED BY A 13 mm DIAMETER BRASS PROJECTILE AT A VELOCITY OF 850 m/sec.

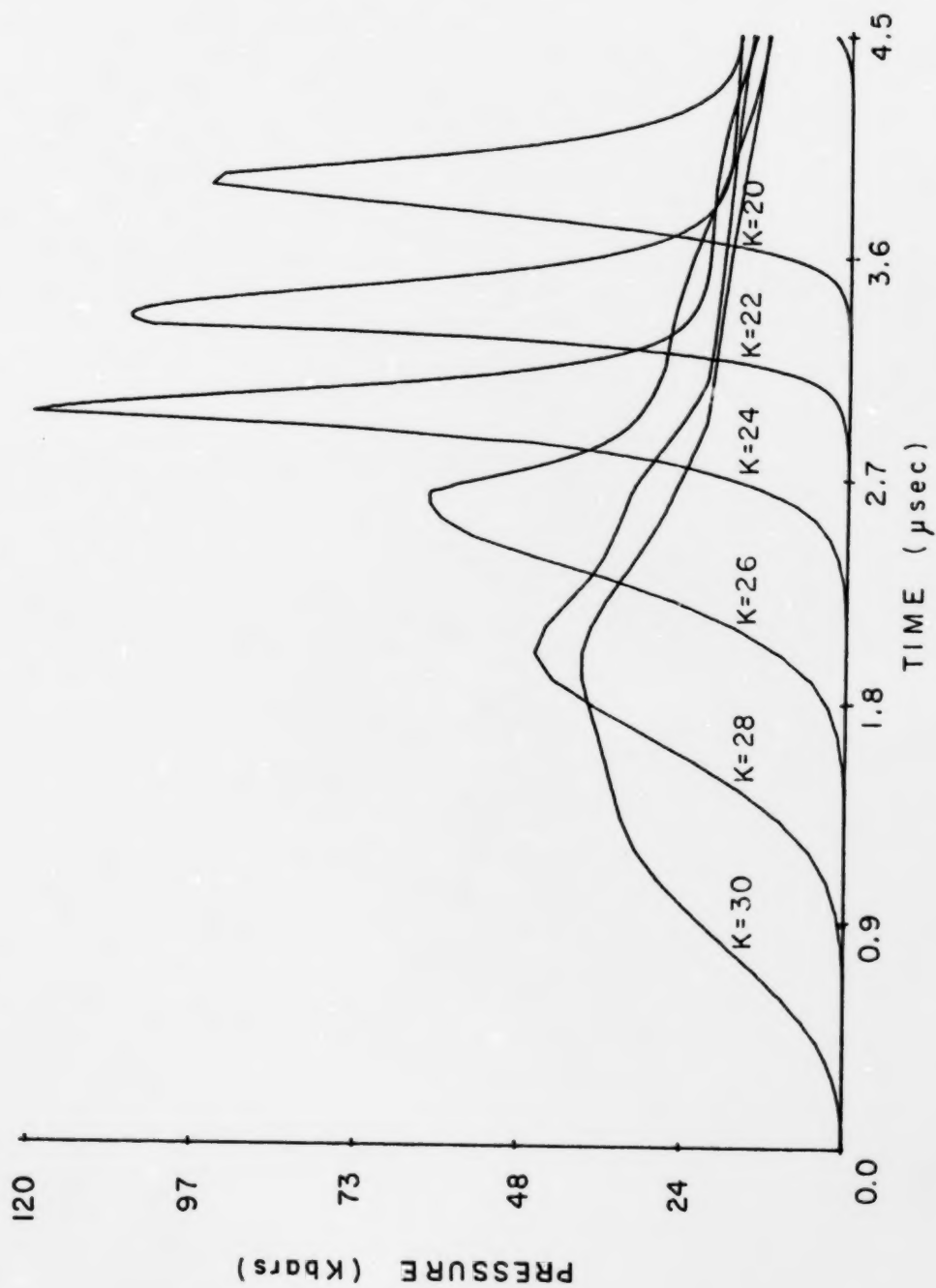


FIGURE 00 : PRESSURE-TIME HISTORIES FOR EMULSION B IMPACTED BY A 1.5 mm DIAMETER BRASS PROJECTILE AT A VELOCITY OF 900 m/sec.

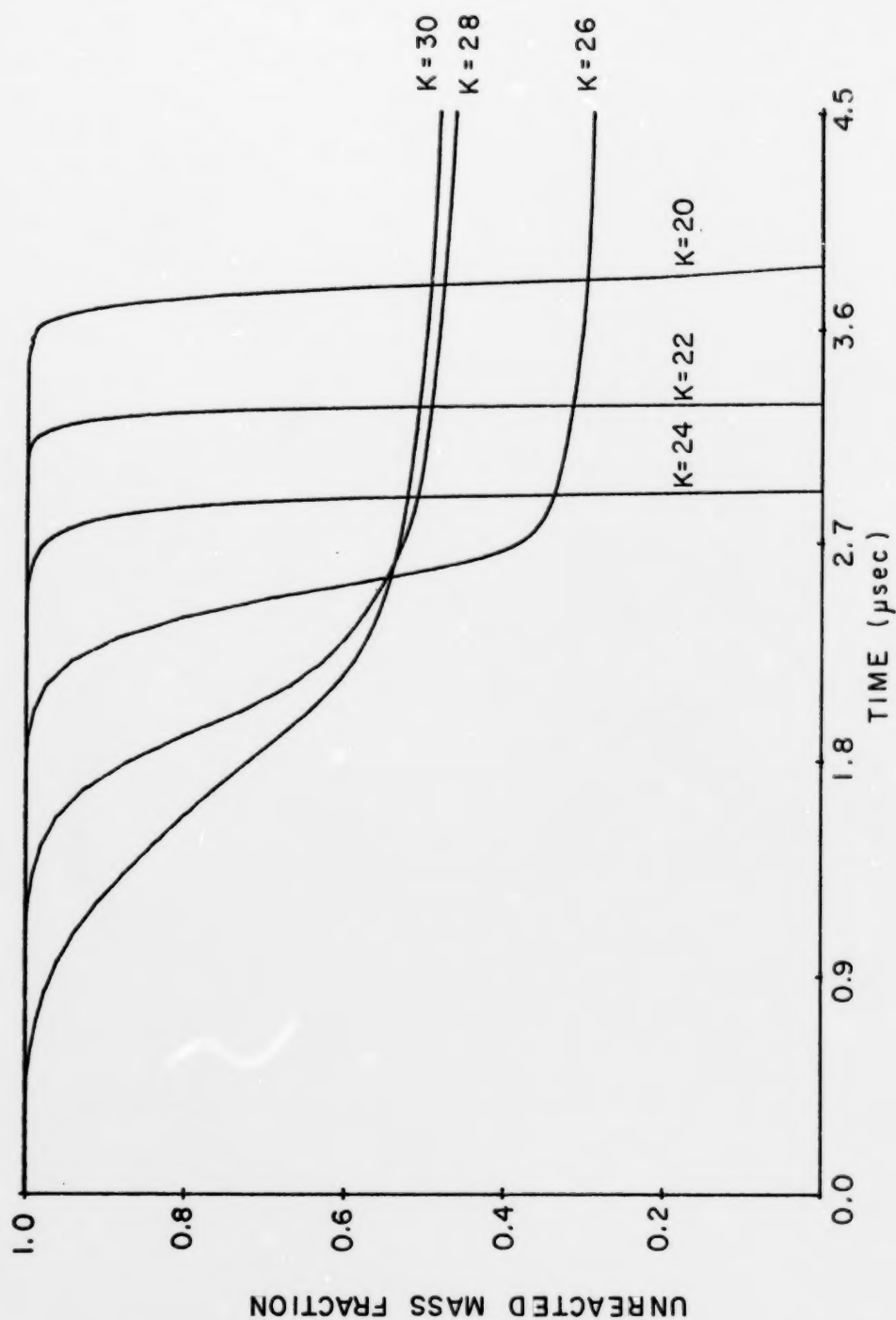


FIGURE 91: MASS FRACTION OF UNREACTED EXPLOSIVE VERSUS TIME FOR EMULSION B IMPACTED BY A 1.3 mm DIAMETER BRASS PROJECTILE AT A VELOCITY OF 900 m/sec.

TABLE 7.12: CALCULATED AND EXPERIMENTAL RESULTS FOR EMULSION B

| PROJECTILE<br>DIAMETER    | EXPERIMENTAL<br>FAILURE VELOCITY<br>(m/sec) | CALCULATED VELOCITY<br>(m/sec) and RESULTS |
|---------------------------|---------------------------------------------|--------------------------------------------|
| 13 mm<br>brass projectile | 800 - 850                                   | 850 marginal<br>900 detonated              |

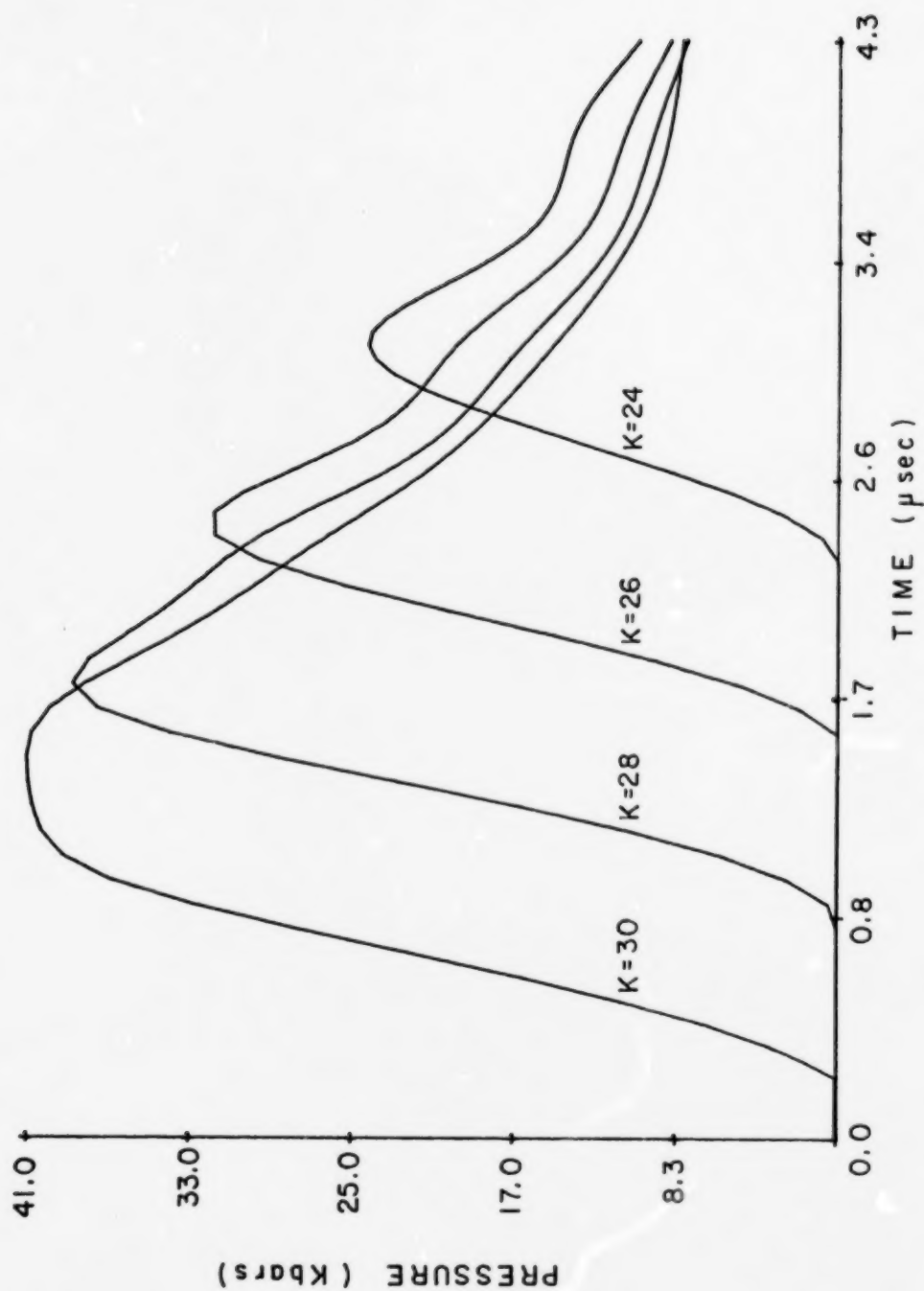


FIGURE 92: PRESSURE-TIME HISTORIES FOR EMULSION C IMPACTED BY A 1.3 mm DIAMETER BRASS PROJECTILE AT A VELOCITY OF 1300 m/sec.

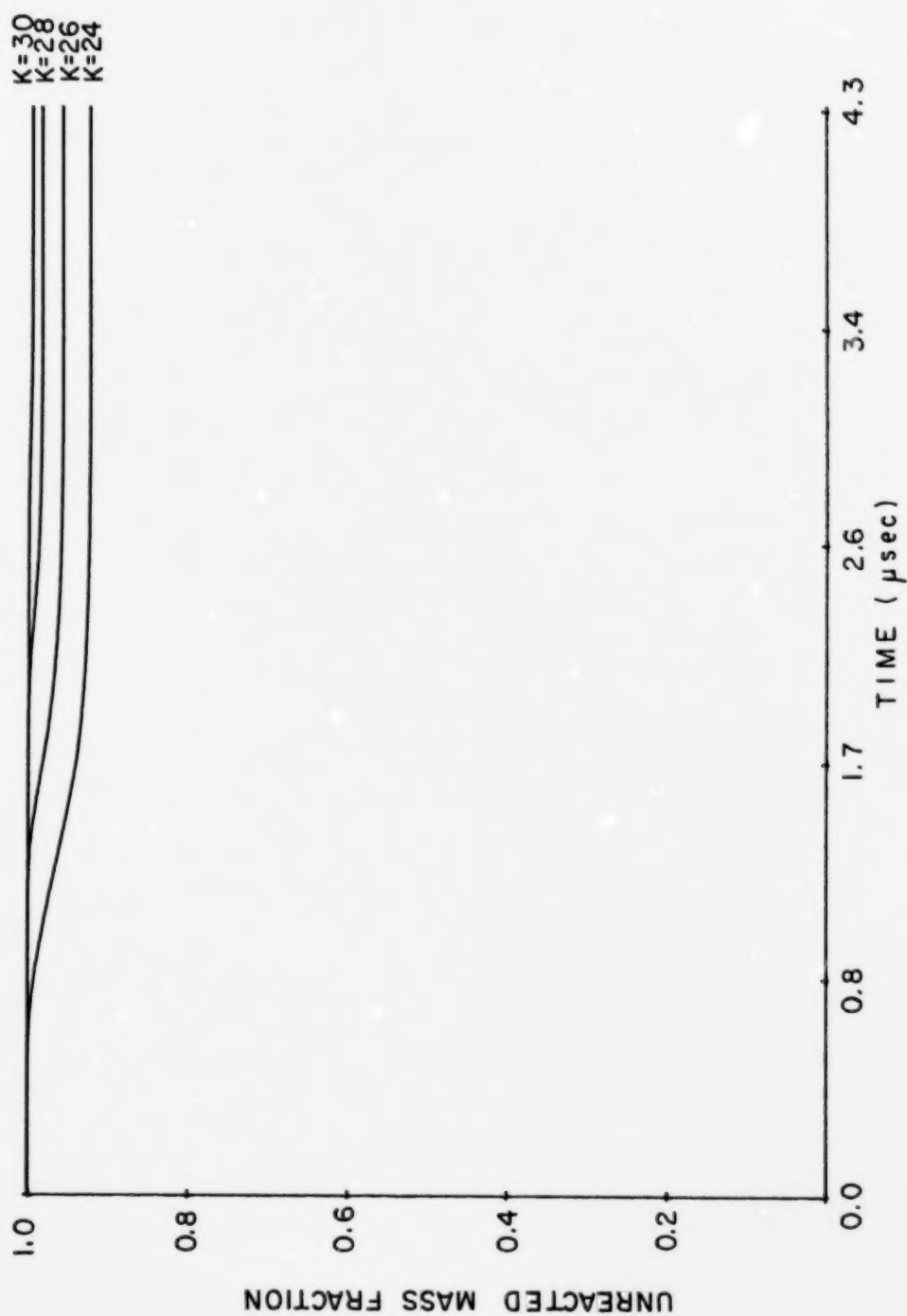


FIGURE 9.3: MASS FRACTION OF UNREACTED EXPLOSIVE TIME FOR EMULSION C IMPACTED BY A 13 mm DIAMETER BRASS PROJECTILE AT A VELOCITY OF 1300 m/sec.

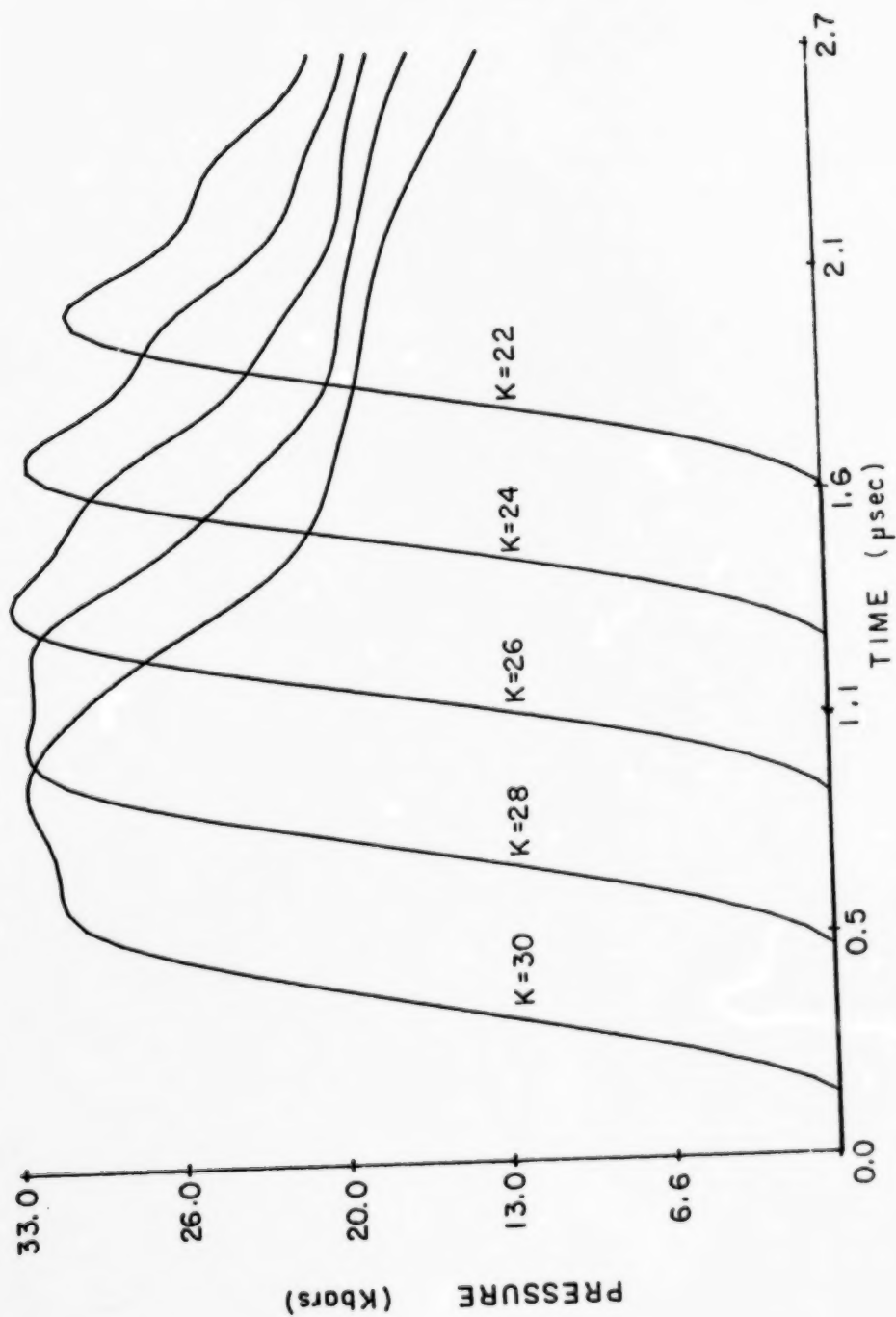


FIGURE 04 : PRESSURE-TIME HISTORIES FOR EMU-505, C IMPACTED BY A 3.2 mm THICK ALUMINUM FLYER PLATE AT A VELOCITY OF 1230 m/sec.

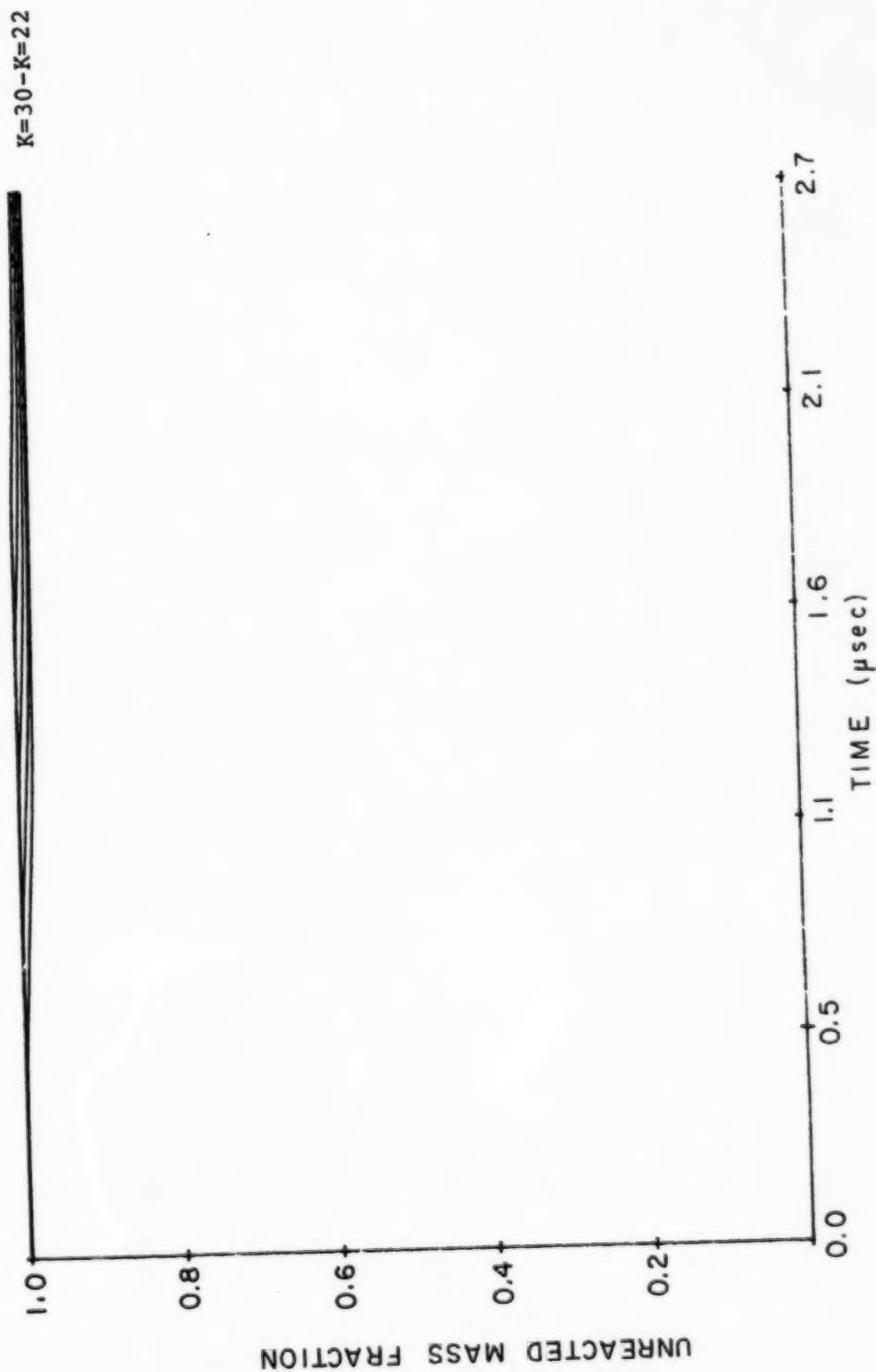


FIGURE 05: MASS FRACTION OF UNREACTED EXPLOSIVE VS. TIME FOR EMULSION C IMPACTED BY A 3.2 mm THICK ALUMINUM FLYER PLATE OF A VELOCITY OF 1230 m/sec.



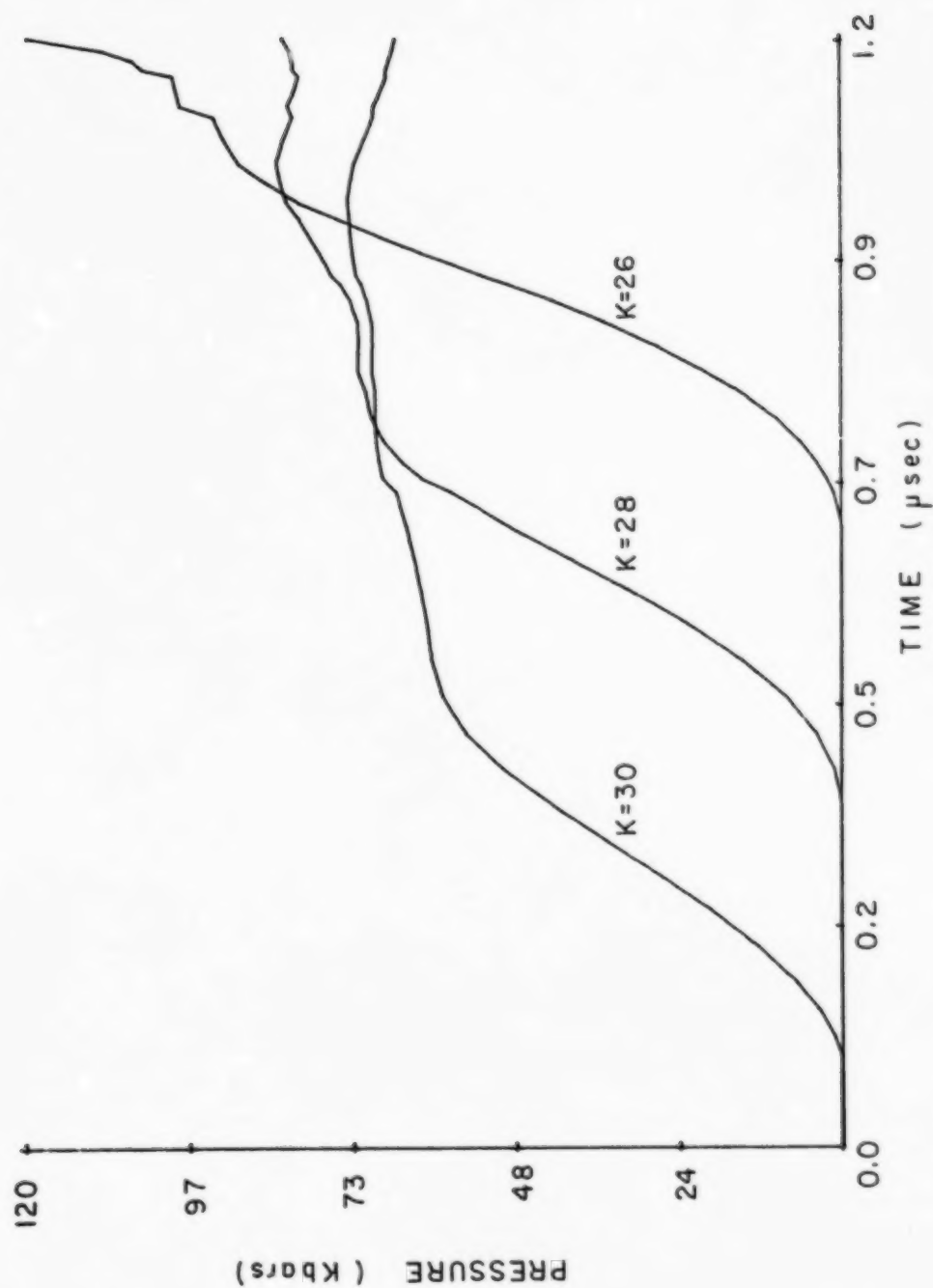


FIGURE 06: PRESSURE TIME HISTORIES FOR EMULSION C IMPACTED BY A 3.2 mm THICK ALUMINUM PLATE AT A VELOCITY OF 1820 m/sec.

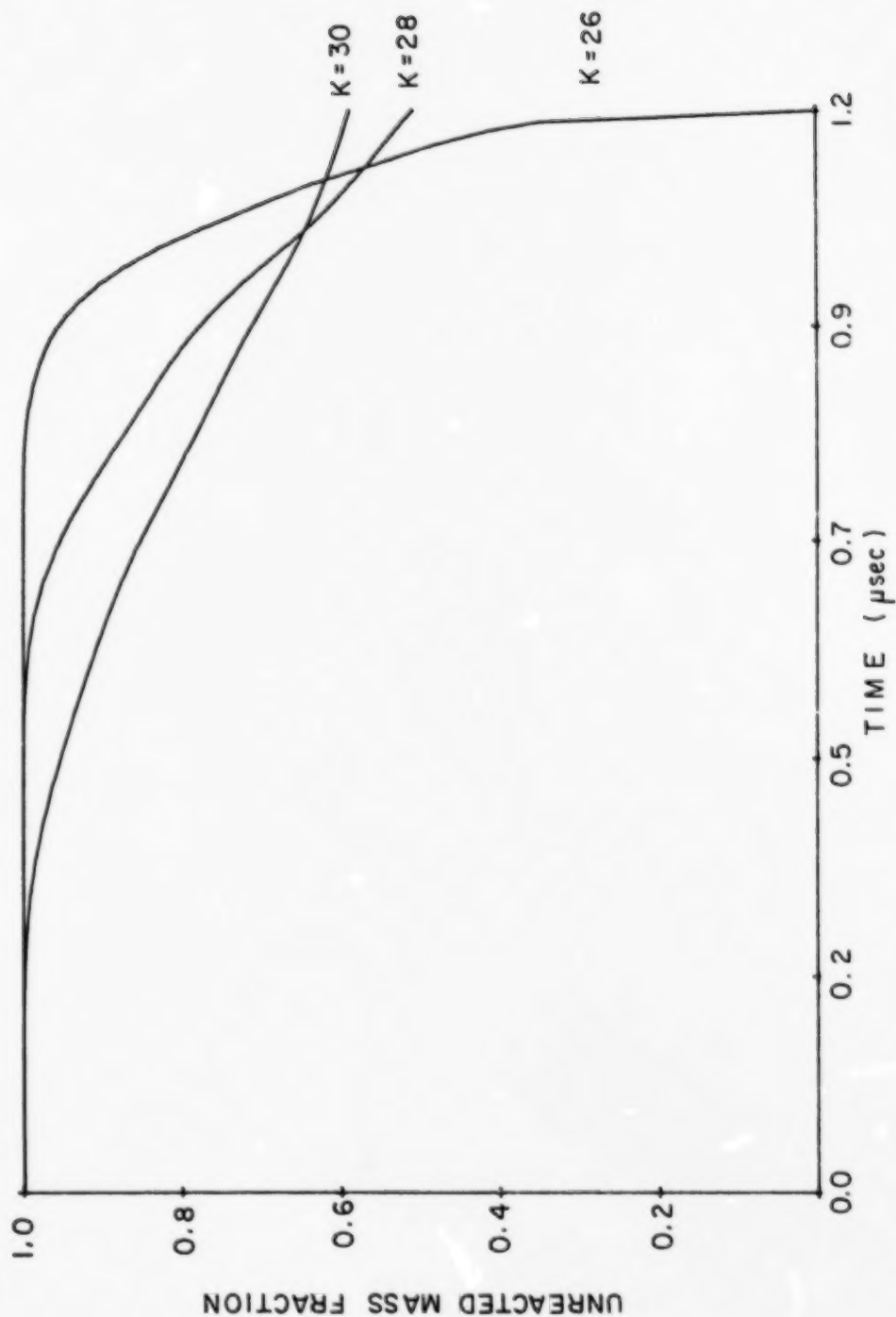


FIGURE 97: MASS FRACTION OF UNREACTED EXPLOSIVE VS. TIME FOR EMULSION C IMPACTED ON A 3.2 mm THICK ALUMINUM PLATE AT VELOCITY OF 1820 m/sec.

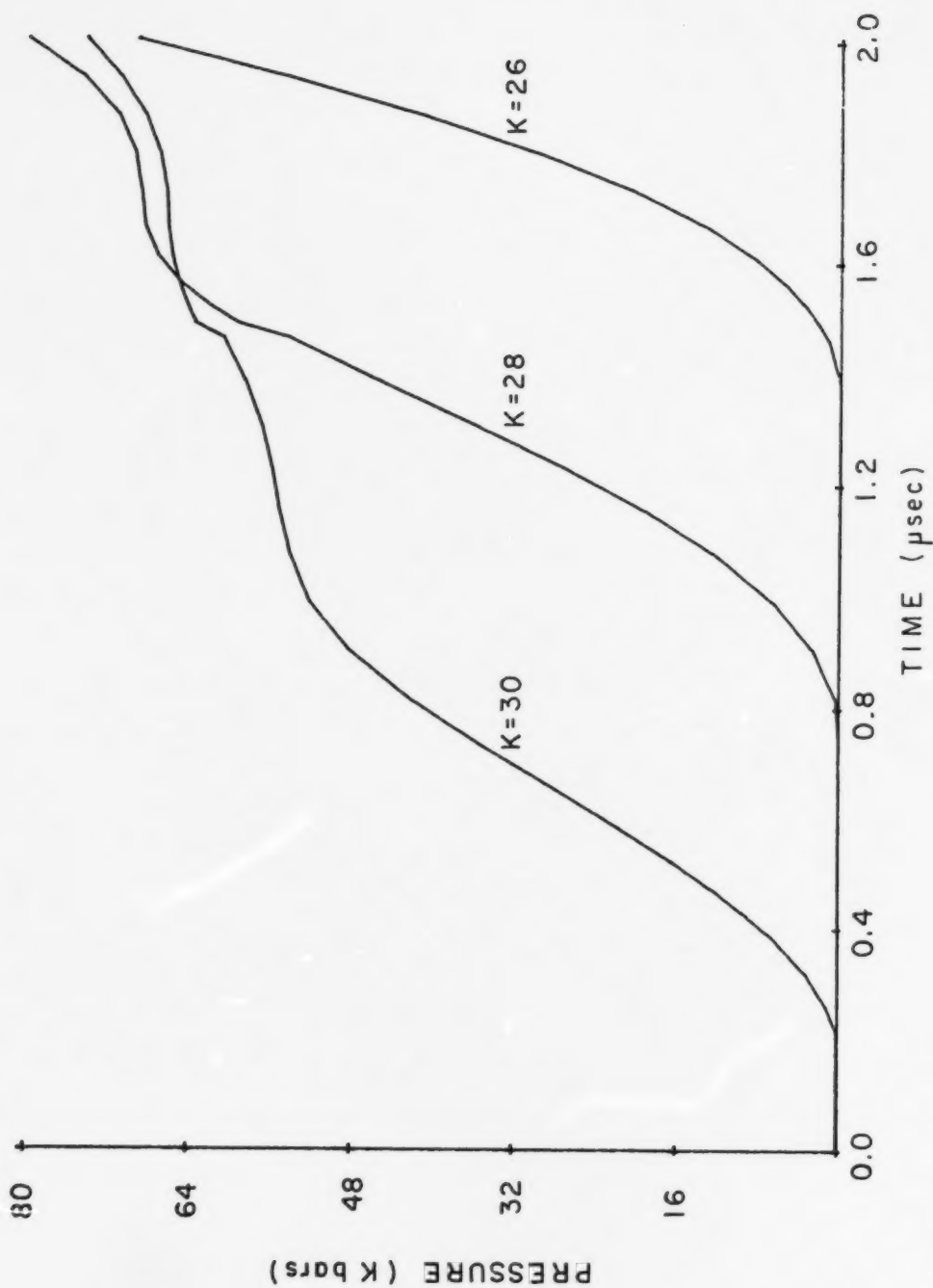


FIGURE 98: PRESSURE-TIME HISTORIES FOR EMULSION C IMPACTED BY A 10 mm THICK ALUMINUM PLATE AT A VELOCITY OF 1000 m/sec.

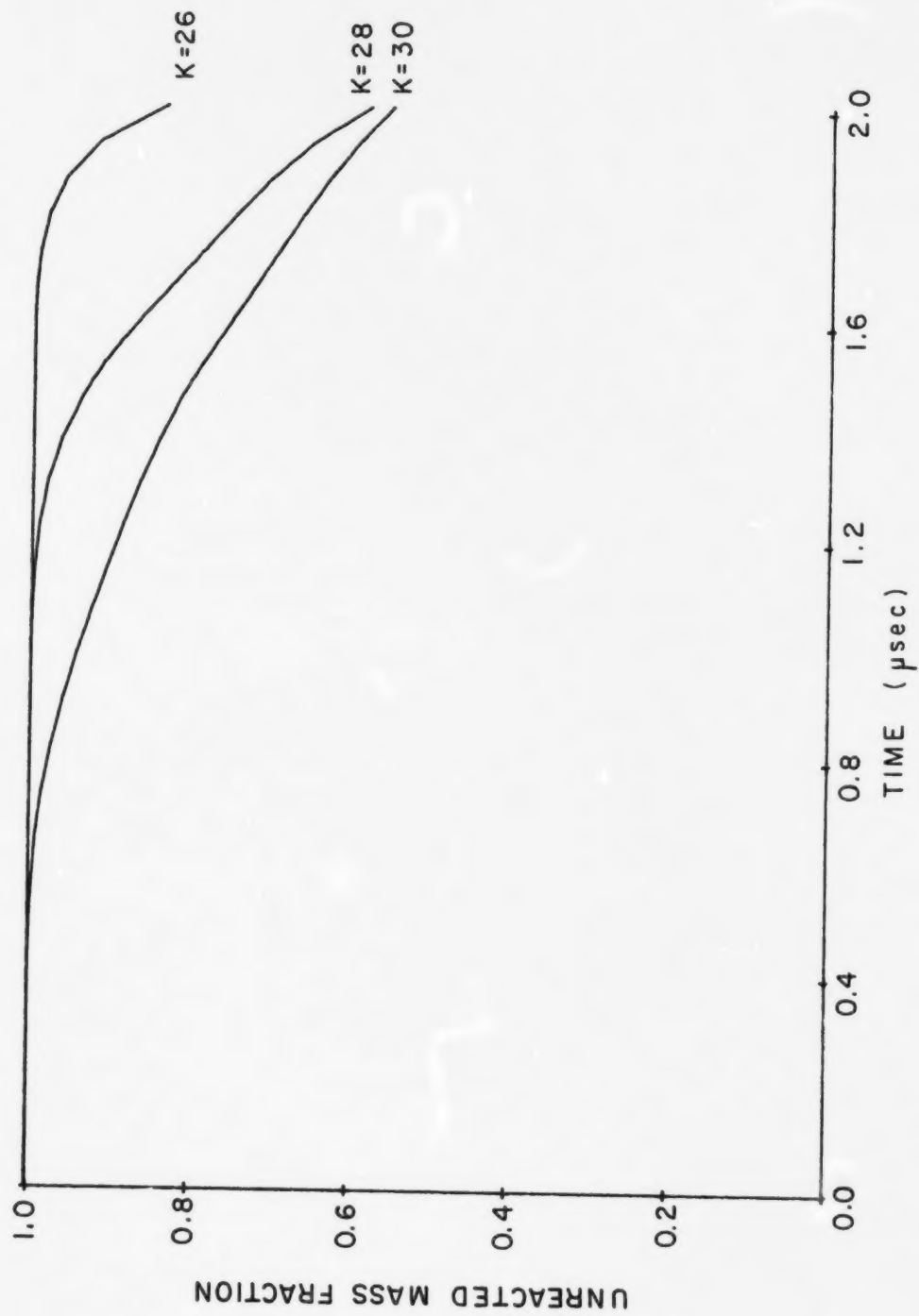


FIGURE 99: MASS FRACTION OF UNREACTED EXPLOSIVE VS. TIME FOR EMULSION C IMPACTED BY A 10 mm THICK ALUMINUM PLATE OF A VELOCITY OF 1000 m/sec.

TABLE 7.13: CALCULATED AND EXPERIMENTAL RESULTS FOR EMULSION C

| IMPACTOR                             | EXPERIMENTAL<br>VELOCITY (m/sec)<br>AND RESULT | CALCULATED VELOCITY<br>(m/sec) and RESULT |
|--------------------------------------|------------------------------------------------|-------------------------------------------|
| 13 mm diameter<br>brass projectile   | 1320 m/s - failed                              | 1320 m/s - failed                         |
| 3.2 mm thick<br>Aluminum flyer plate | 1230 - failed<br>1820 - detonated              | 1230 - failed<br>1820 - detonated         |
| 10 mm thick<br>Aluminum flyer plate  | 1660 - detonated                               | 1660 - detonated                          |

### Slurry A

The impact of the cap sensitive Slurry A by large aluminum projectiles was modelled. The results of the calculations are shown in Figures 100 to 113 as pressure time and corresponding unreacted mass fraction time curves. The results are also summarized and compared against the experimental ones in Table 7.14. The element size in the grid was 1 mm x 1 mm in the cases of targets impacted by projectiles having a diameter of 2.5 cm and 2 mm x 2 mm in the rest of the cases.

### Slurry B

The impact of Slurry B by large aluminum projectiles was modelled. The results are presented in Figures 114 to 123 and in Table 7.15 where they are compared against the experimental ones.

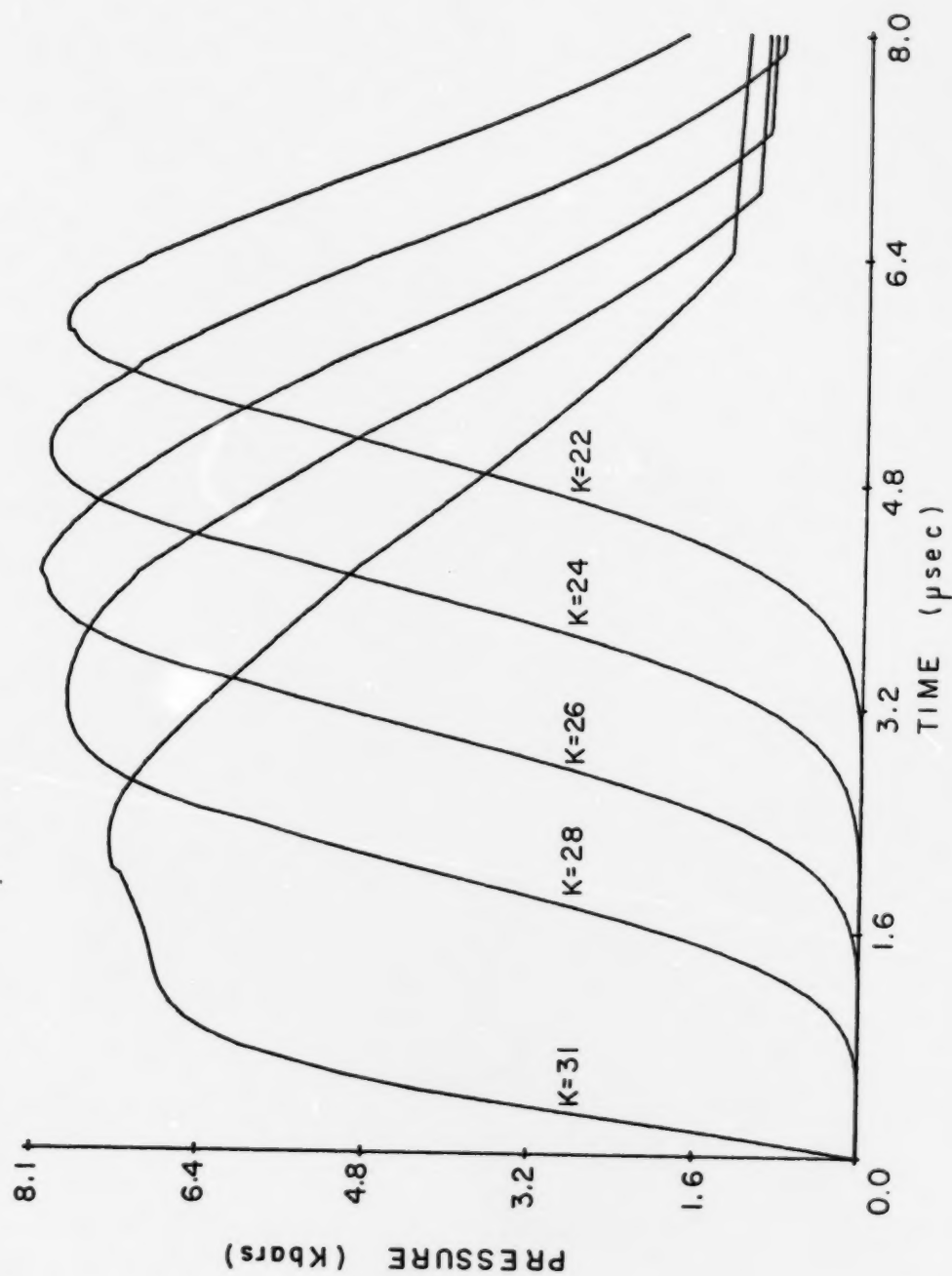


FIGURE 100: PRESSURE-TIME HISTORIES FOR SLURRY A IMPACTED BY A 2.5 cm DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF 300 m/sec.

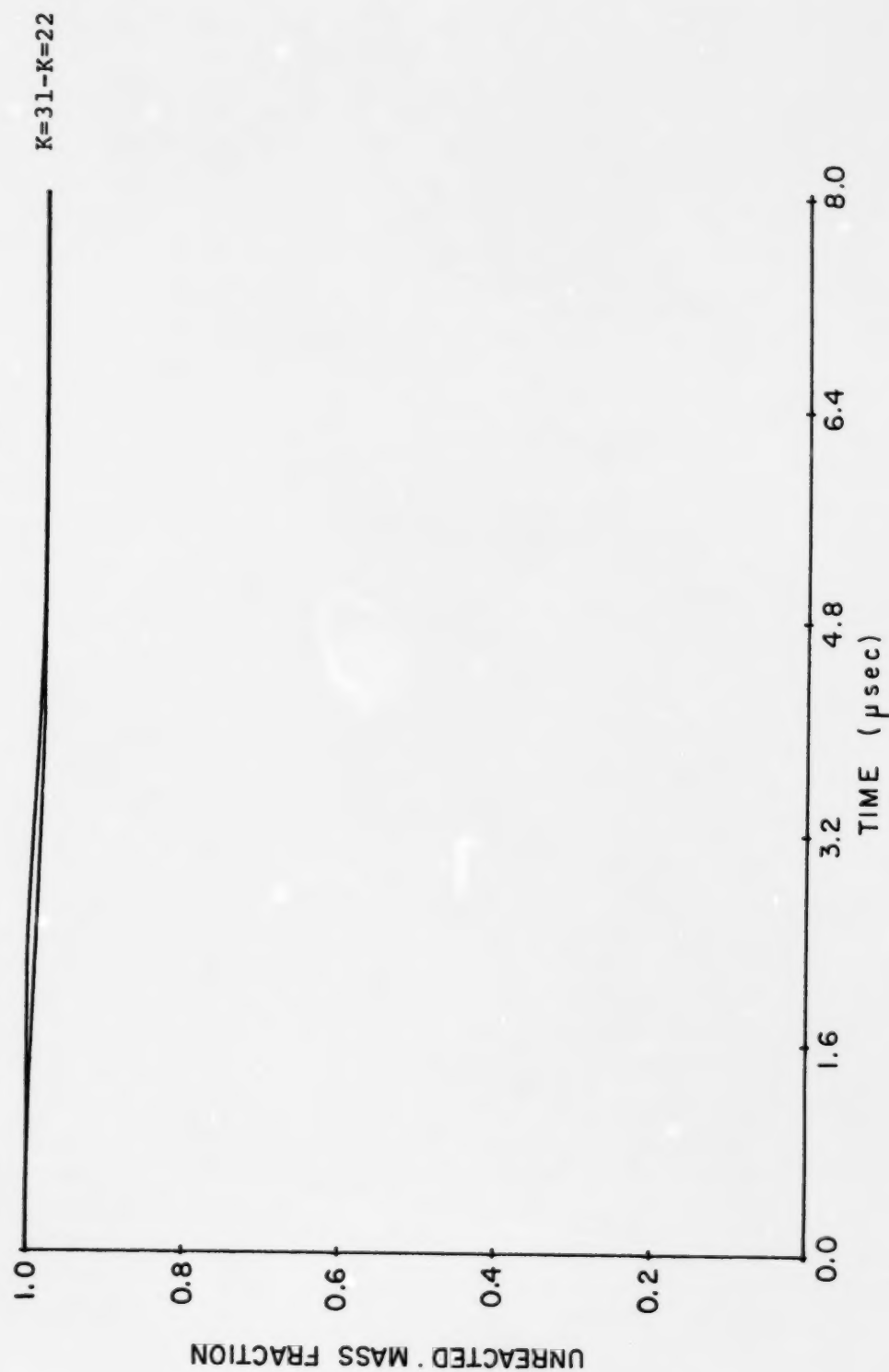


FIGURE 101 : MASS FRACTION OF UNREACTED EXPLOSIVE VS. TIME FOR SLURRY A IMPACTED BY A 2.5 cm DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF 300 m/sec.



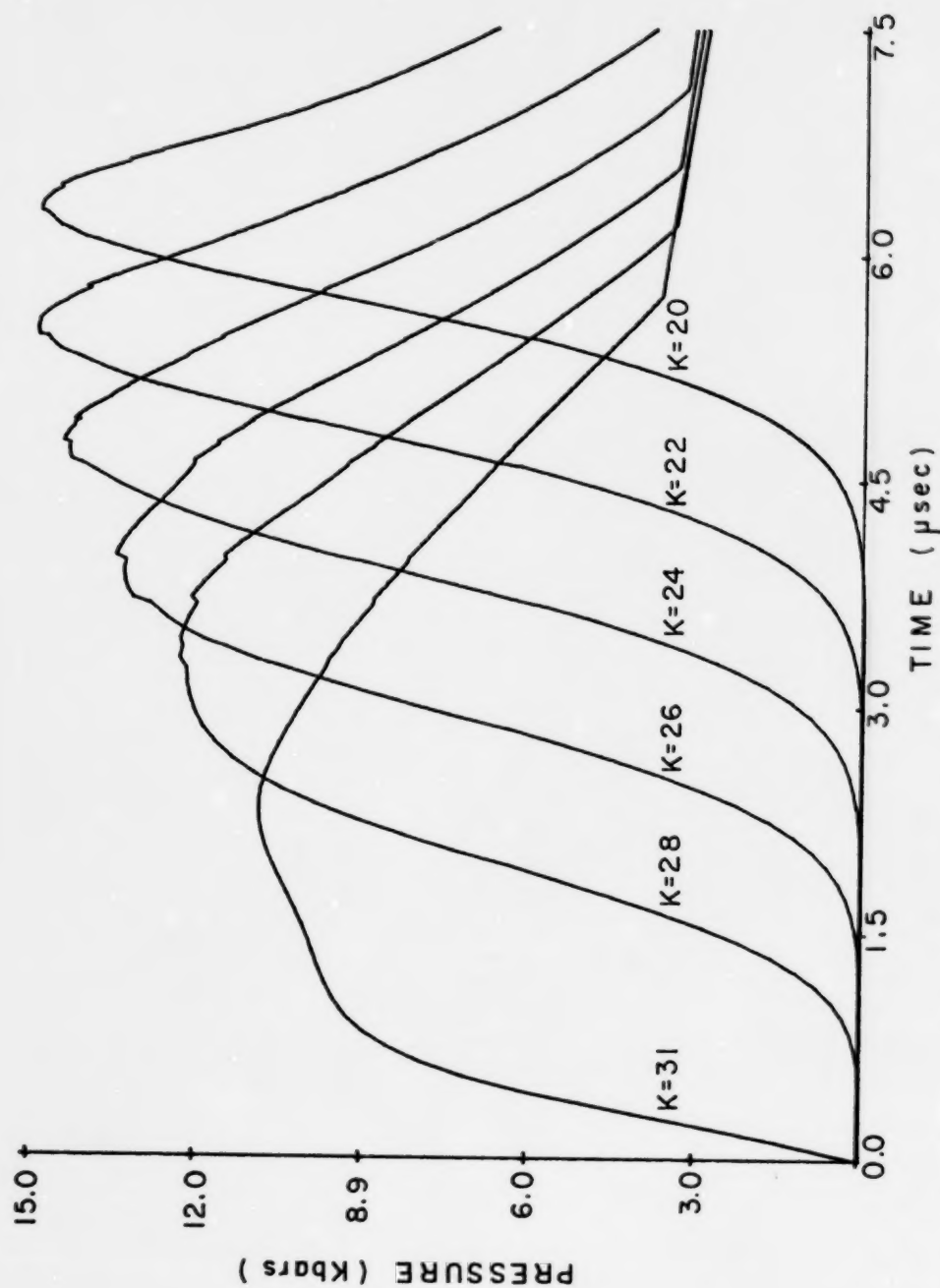


FIGURE 102: PRESSURE-TIME HISTORIES FOR SLURRY IMPACTED BY A 2.5 cm DIAMETER ALUMINUM PROJECTILE OF A VELOCITY OF 420 m/sec.

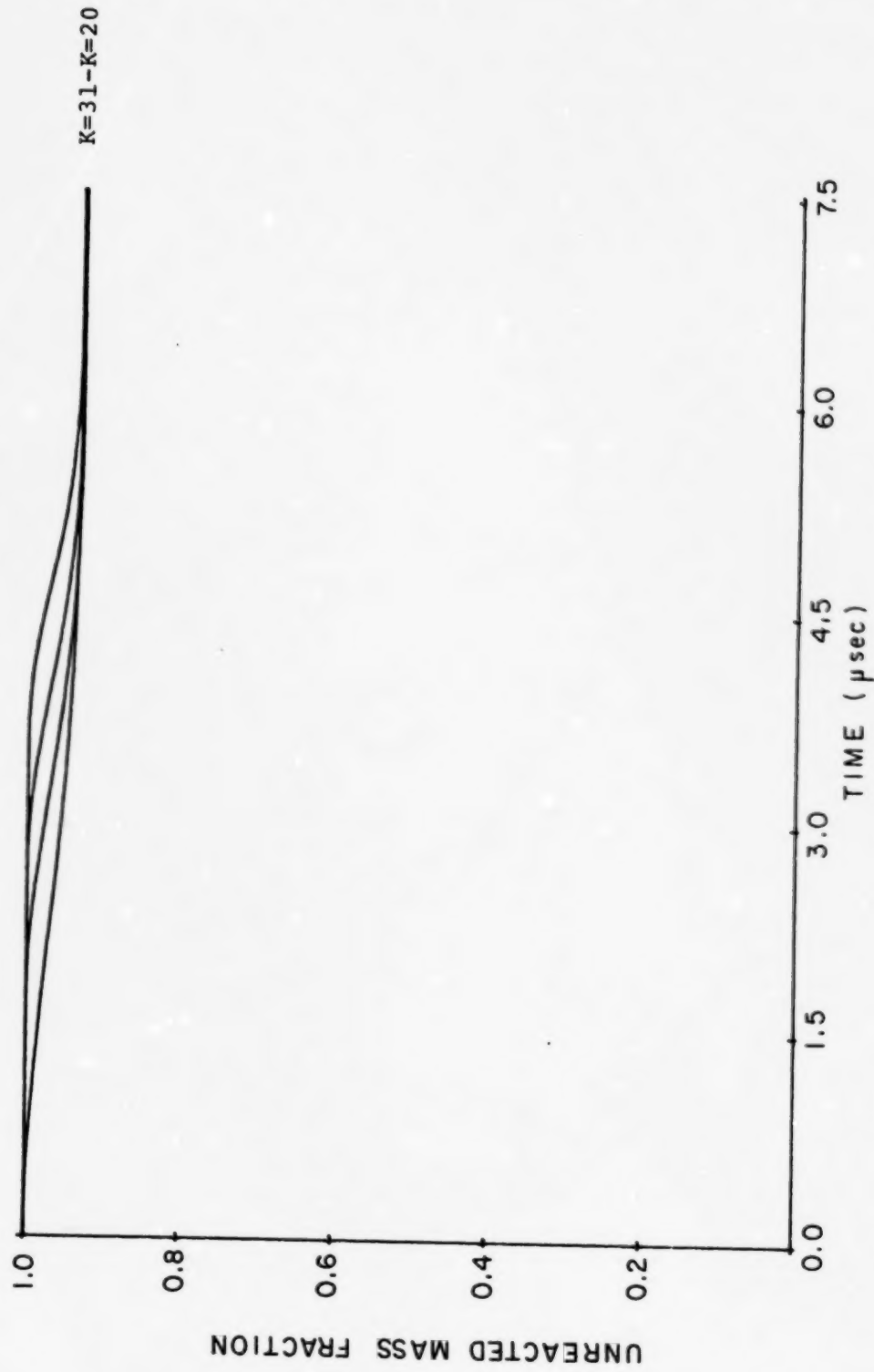


FIGURE 10.3: MASS FRACTION OF UNREACTED EXPLOSIVE VS. TIME FOR SLURRY A IMPACTED BY A 2.5 cm DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF 420 m/sec.

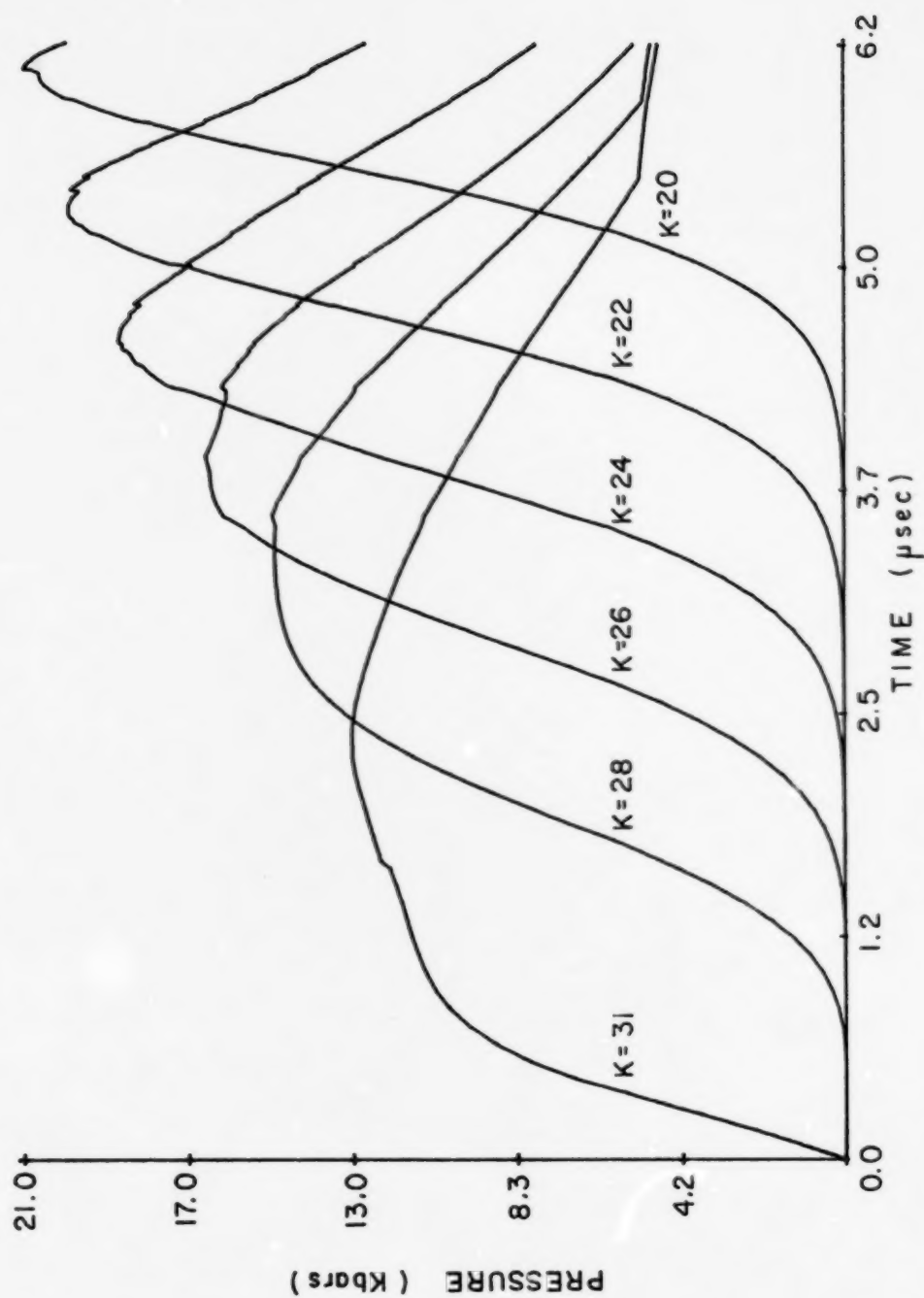


FIGURE 104: PRESSURE-TIME HISTORIES FOR SLURRY A IMPACTED BY A 2.5 CM DIAMETER ALUMINUM PROJECTILE OF A VELOCITY OF 400 m/sec.

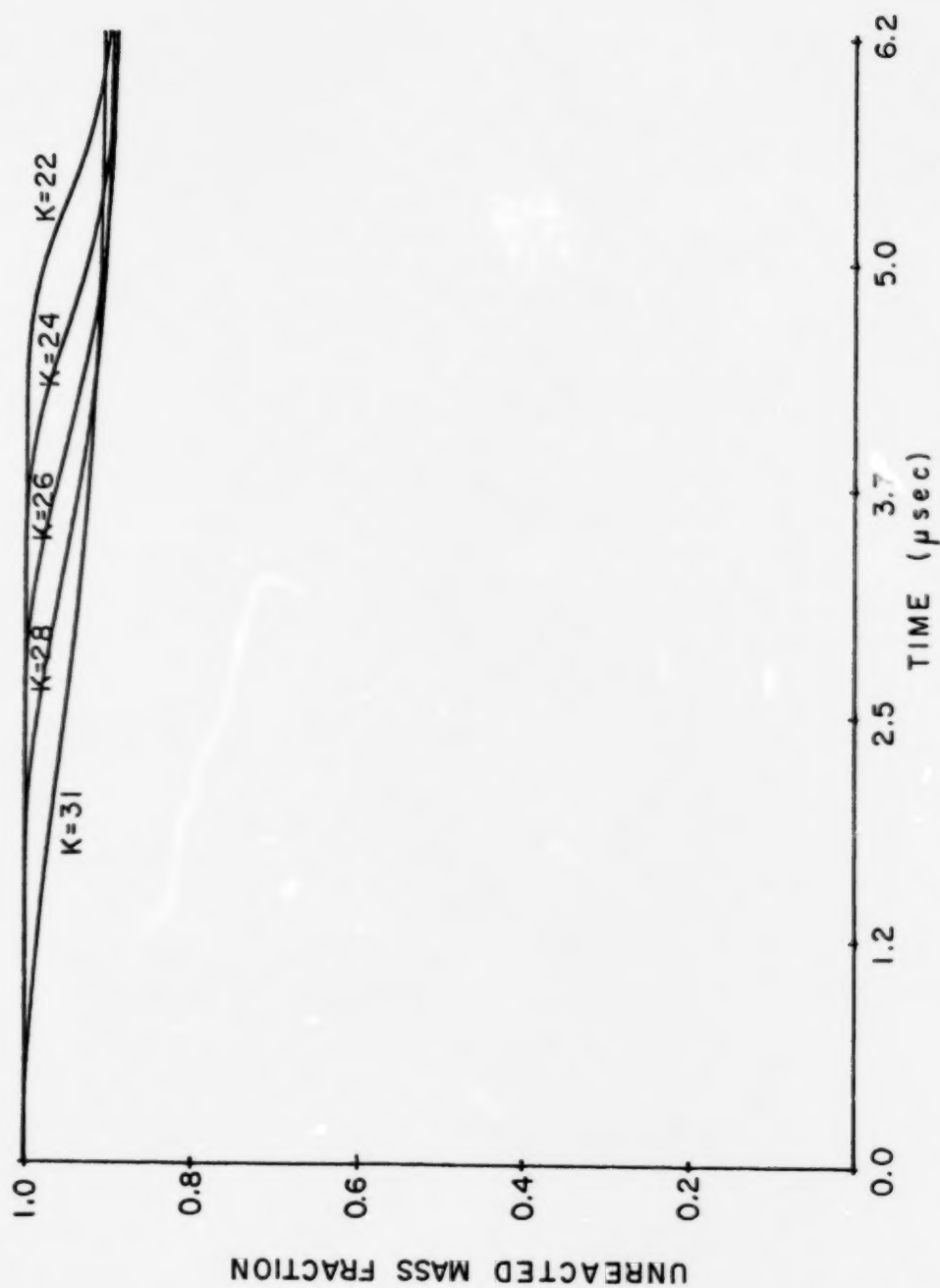


FIGURE 105: MASS FRACTION OF UNREACTED EXPLOSIVE VS. TIME FOR SLURRY A IMPACTED BY A 2.5 cm DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF 400 m/sec.

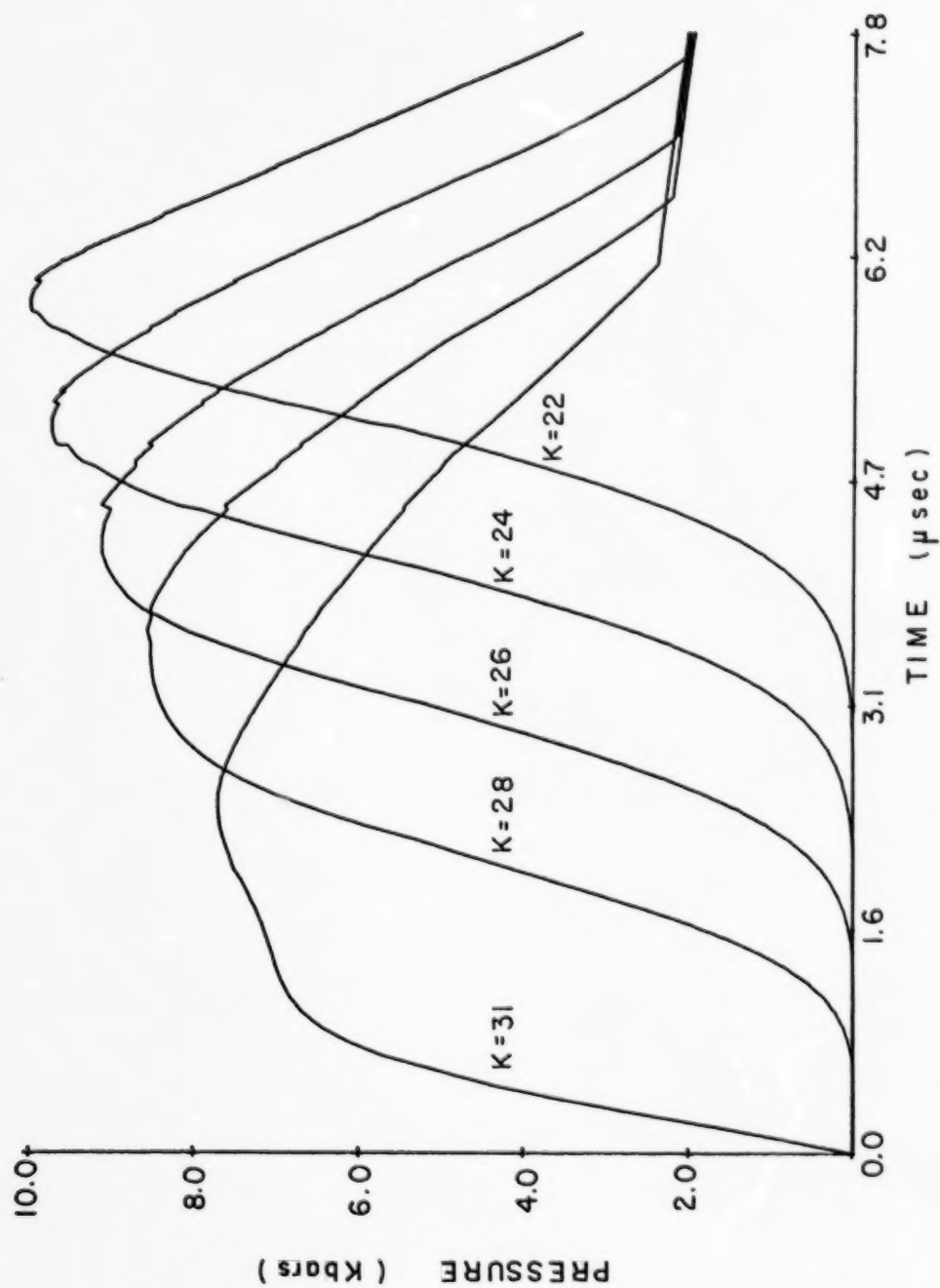


FIGURE 106: PRESSURE-TIME HISTORIES FOR GLUEY A IMPACTED BY A 5.1 cm DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF 300 m/sec.

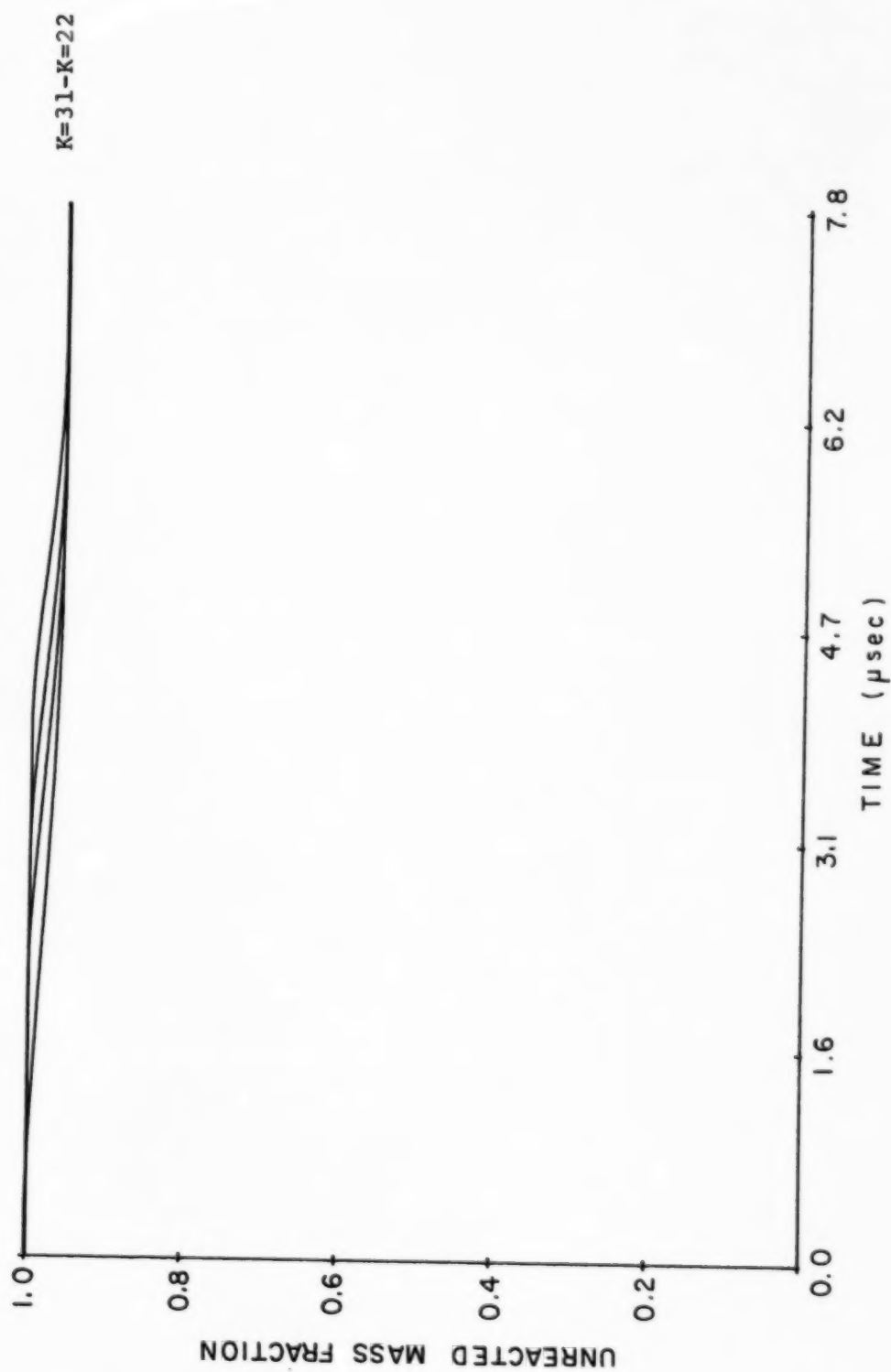


FIGURE 107: MASS FRACTION OF UNREACTED EXPLOSIVE VS. TIME FOR SLUGS: A IMPACTED BY A 5.1 cm DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF 300 m/sec.

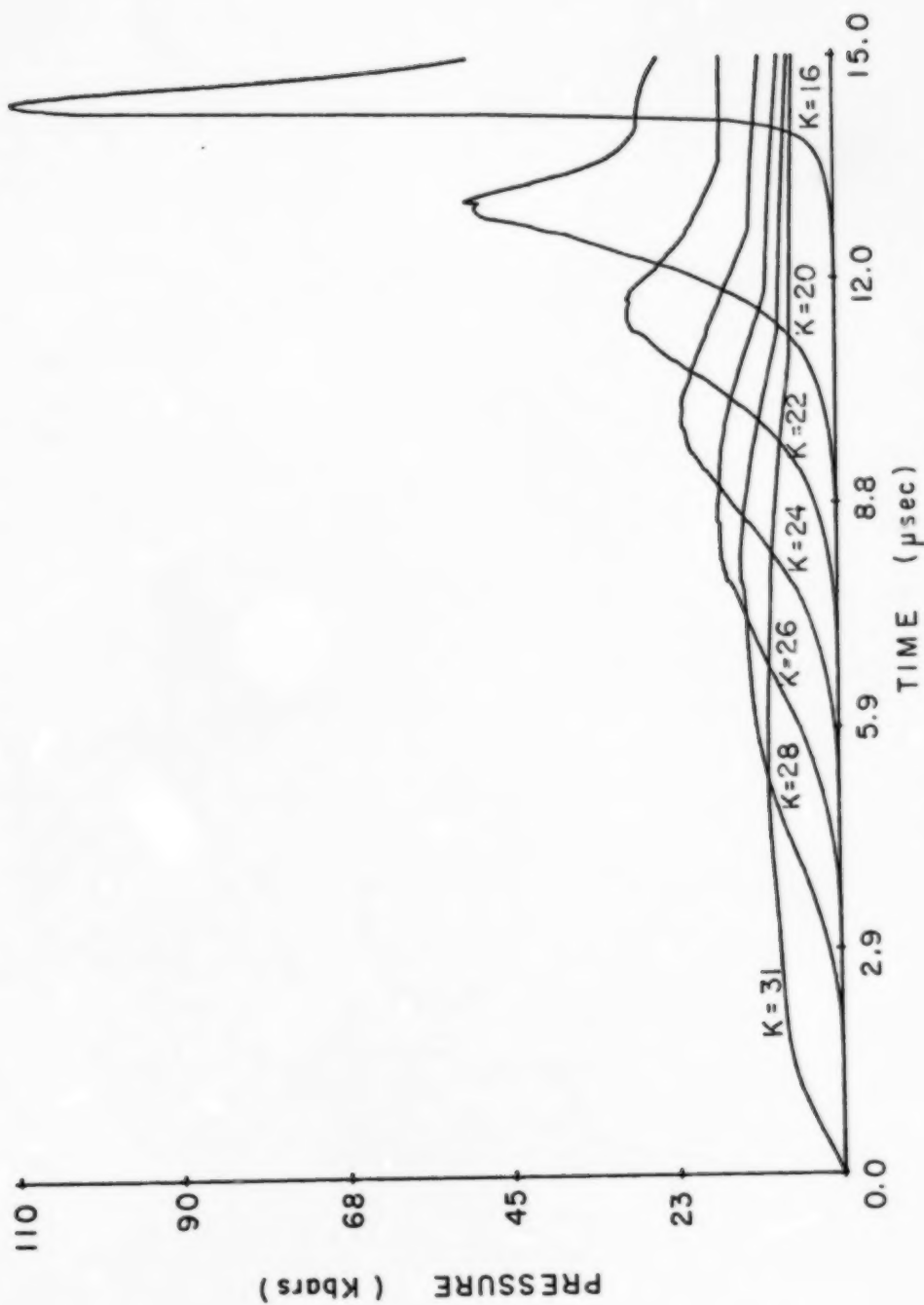


FIGURE 108: PRESSURE TIME HISTORIES FOR SLUGS A IMPACTED BY  
A 5.1 cm DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF  
300 m/sec.

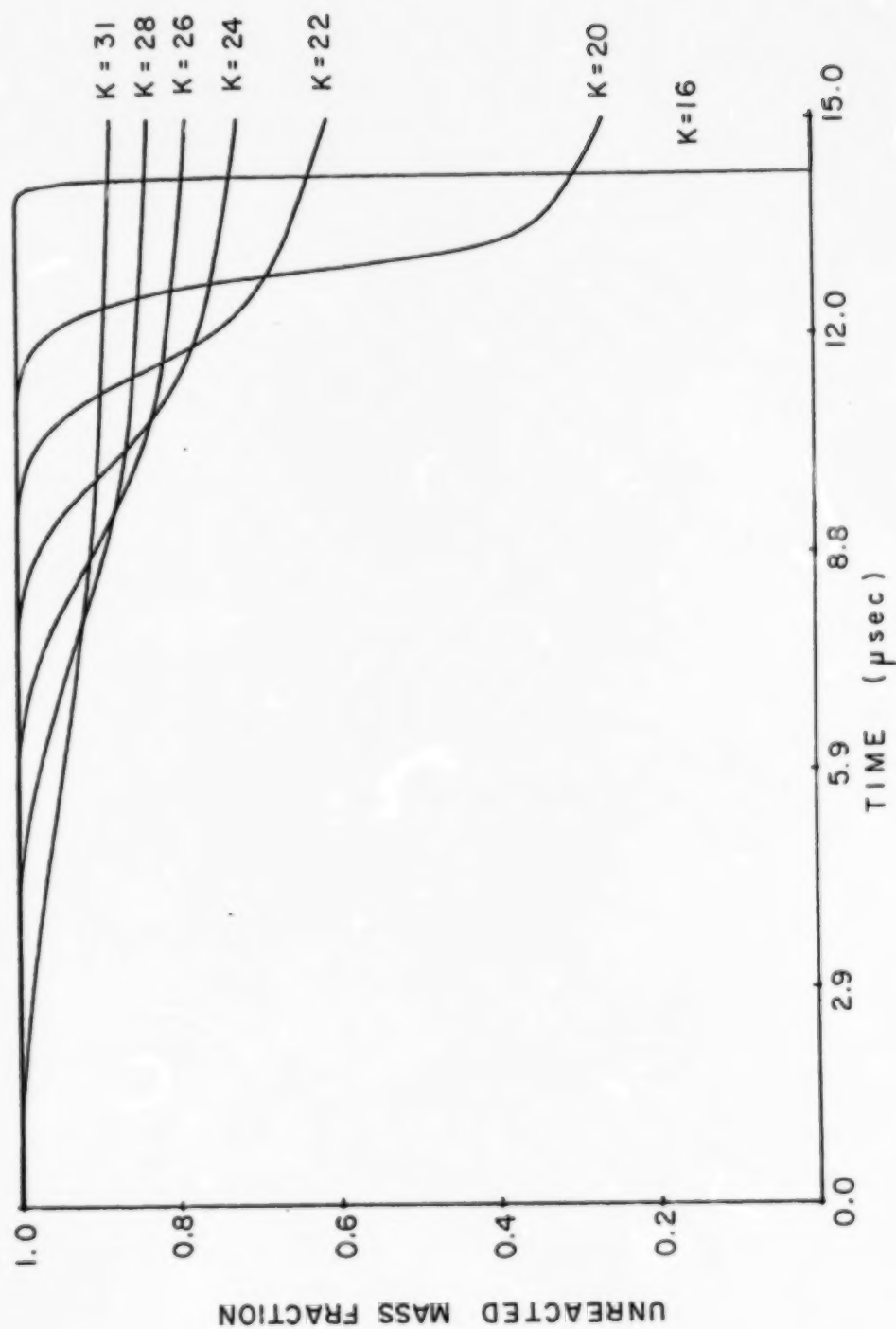


FIGURE 11.3: MASS FRACTION OF UNREACTED EXPLOSIVE VS. TIME FOR GURRY A IMPACTED BY A 5.1 CM DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF 300 m/sec.



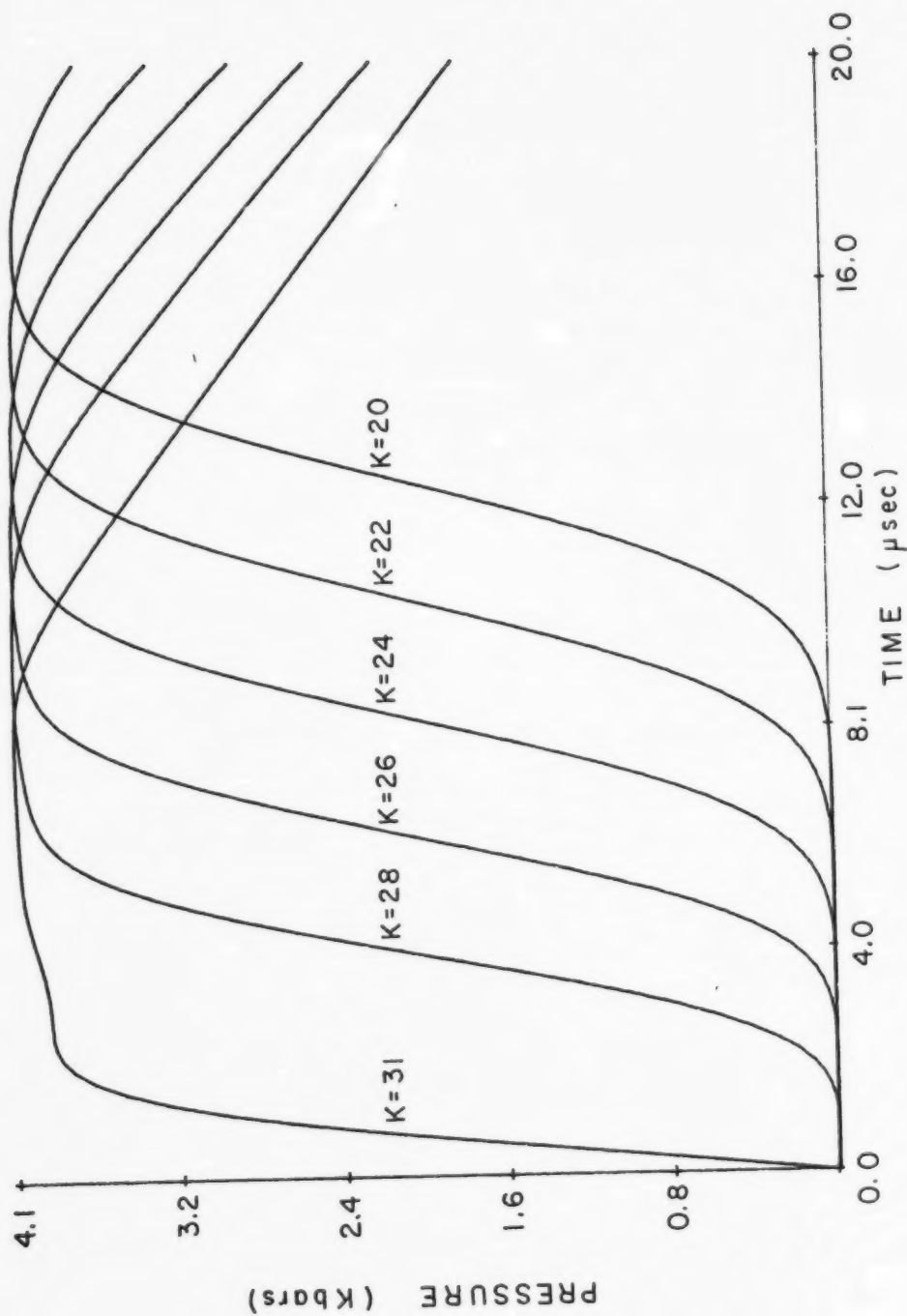


FIGURE 110: PRESSURE TIME HISTORIES FOR SLURRY A IMPACTED BY A 10.2 cm DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF 200 m/sec.

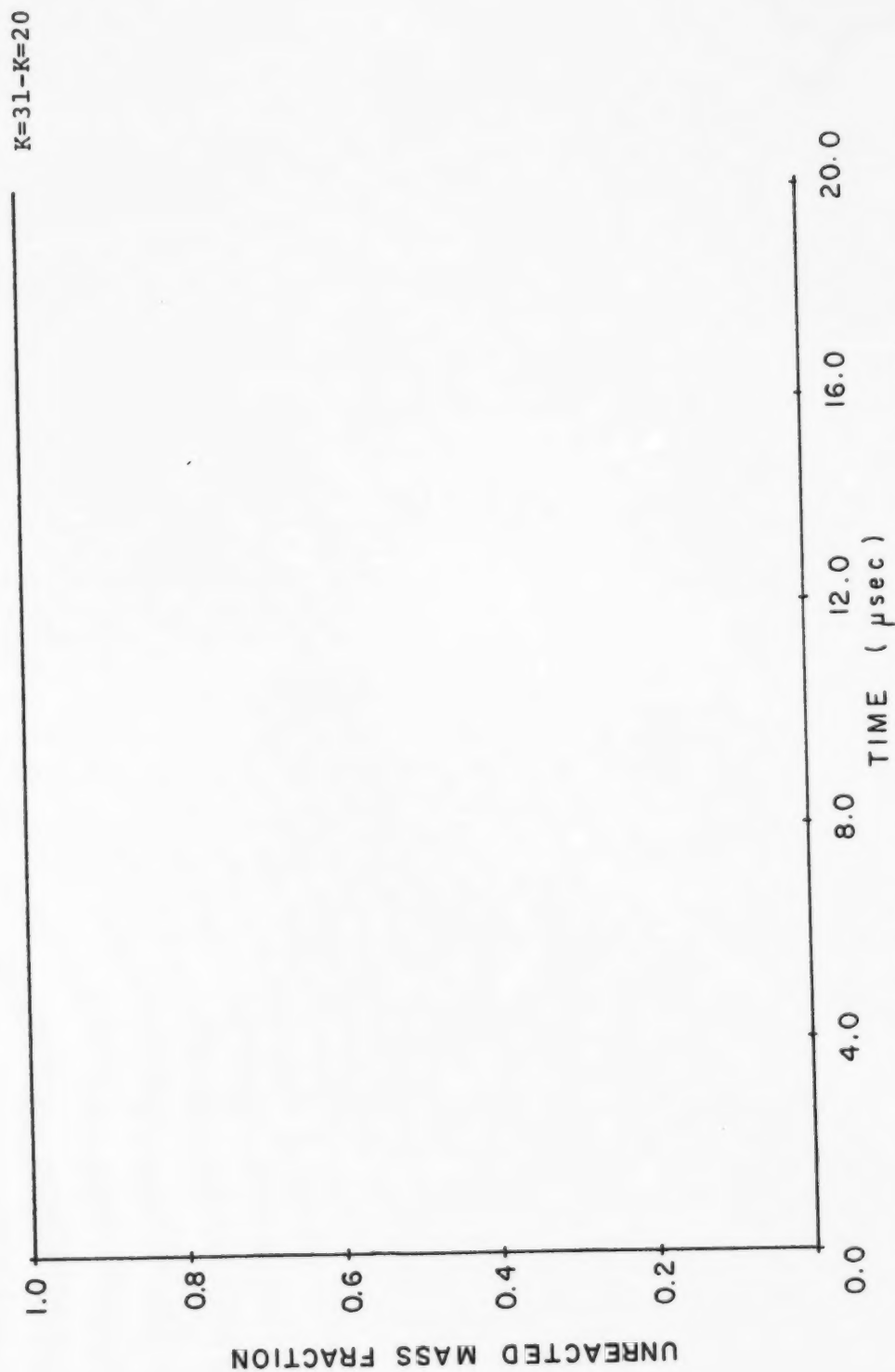


FIGURE 111: MASS FRACTION OF UNREACTED EXPLOSIVE VS. TIME FOR SLURRY A  
IMPACTED BY A 10.2 cm DIAMETER ALUMINUM PROJECTILE AT A VELOCITY  
OF 200 m/sec.

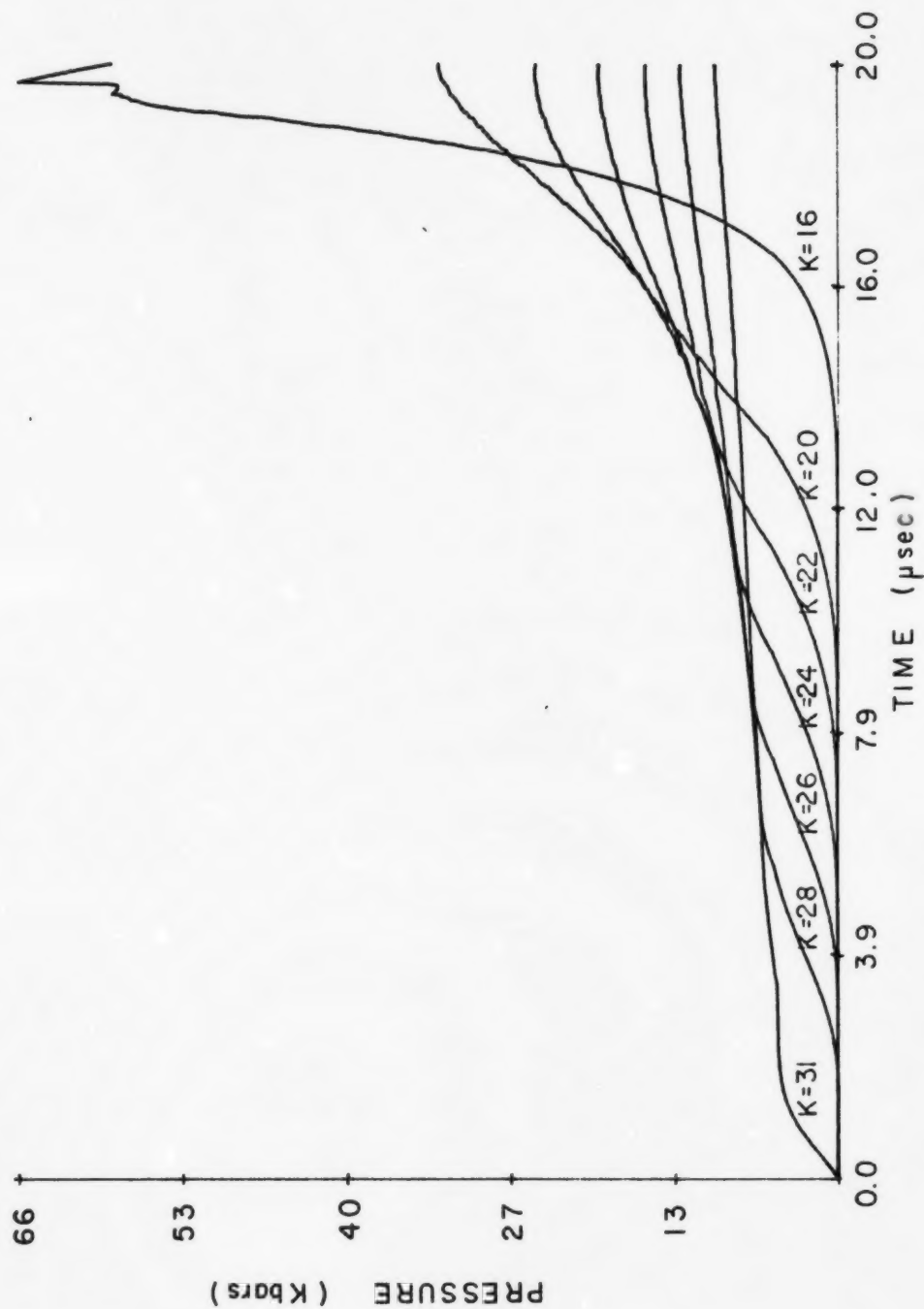


FIGURE 112: PRESSURE TIME HISTORIES FOR GLUR37 A IMPACTED BY A  
10.2 cm DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF  
250 m/sec.

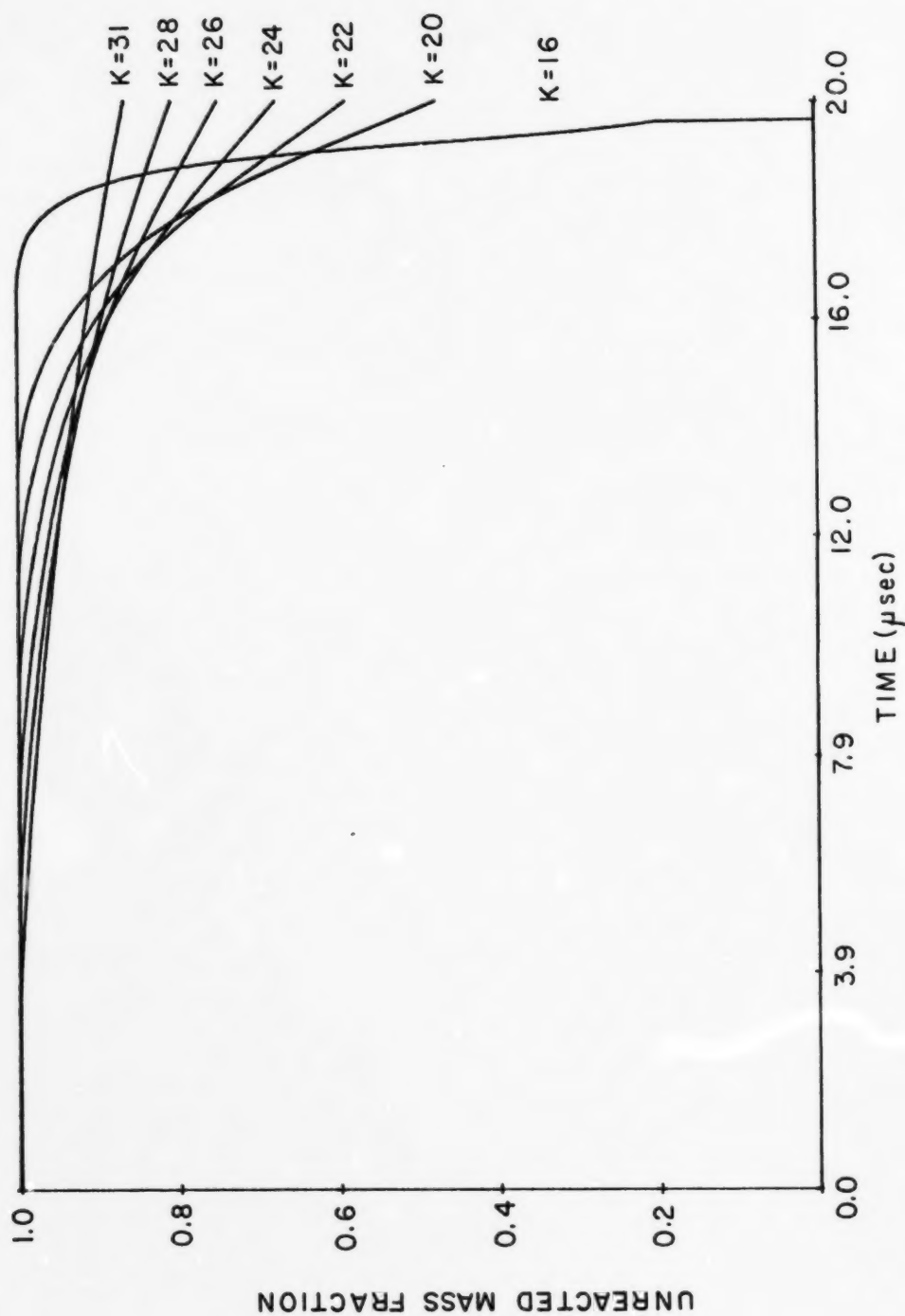


FIGURE 100: MASS FRACTION OF UNREACTED EXPLOSIVE VS. TIME FOR SLURRY : IMPACTED BY A 10.2 cm DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF 250 m/sec.

TABLE 7.14: CALCULATED AND EXPERIMENTAL RESULTS FOR SLURRY A

| IMPACTOR                                                         | EXPERIMENTAL<br>VELOCITY (m/sec)<br>AND RESULT | CALCULATED VELOCITY<br>(m/sec) and RESULT |
|------------------------------------------------------------------|------------------------------------------------|-------------------------------------------|
| Aluminum<br>Projectile<br>(diameter: 2.5 cm<br>length: 5.0 cm)   | 435 - failed<br>447 - detonated                | 300 - failed<br>460 - detonated           |
| Aluminum<br>Projectile<br>(diameter: 5.0 cm<br>length: 10.0 cm)  | 286 - failed<br>337 - detonated                | 300 - failed<br>360 - detonated           |
| Aluminum<br>Projectile<br>(diameter: 10.0 cm<br>length: 13.0 cm) | 200 - failed<br>417 - detonated                | 200 - failed<br>250 - detonated           |

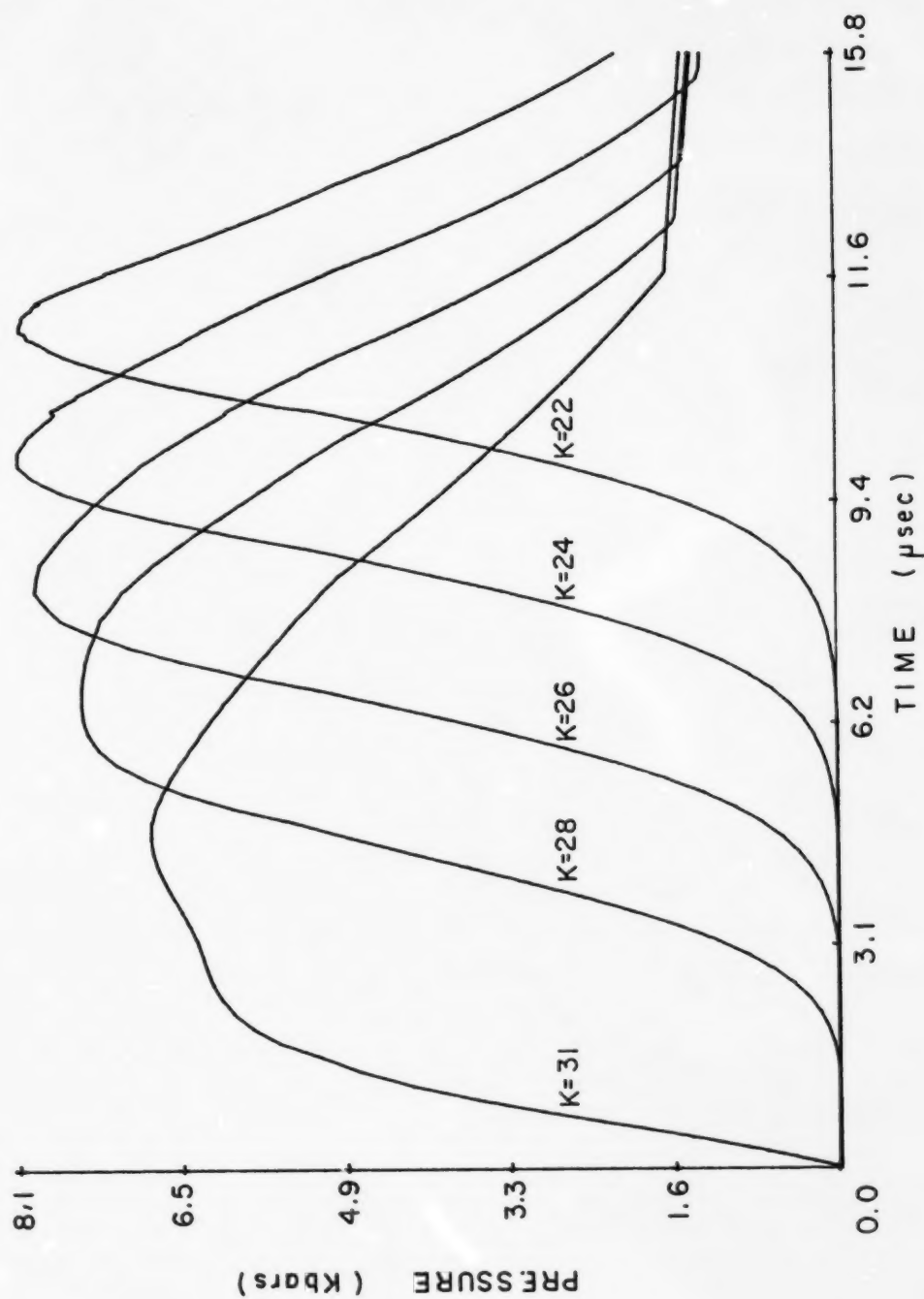


FIGURE 114: PRESSURE TIME HISTORIES FOR SLURRY B IMPACTED BY A 5.0 cm DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF 300 m/sec.

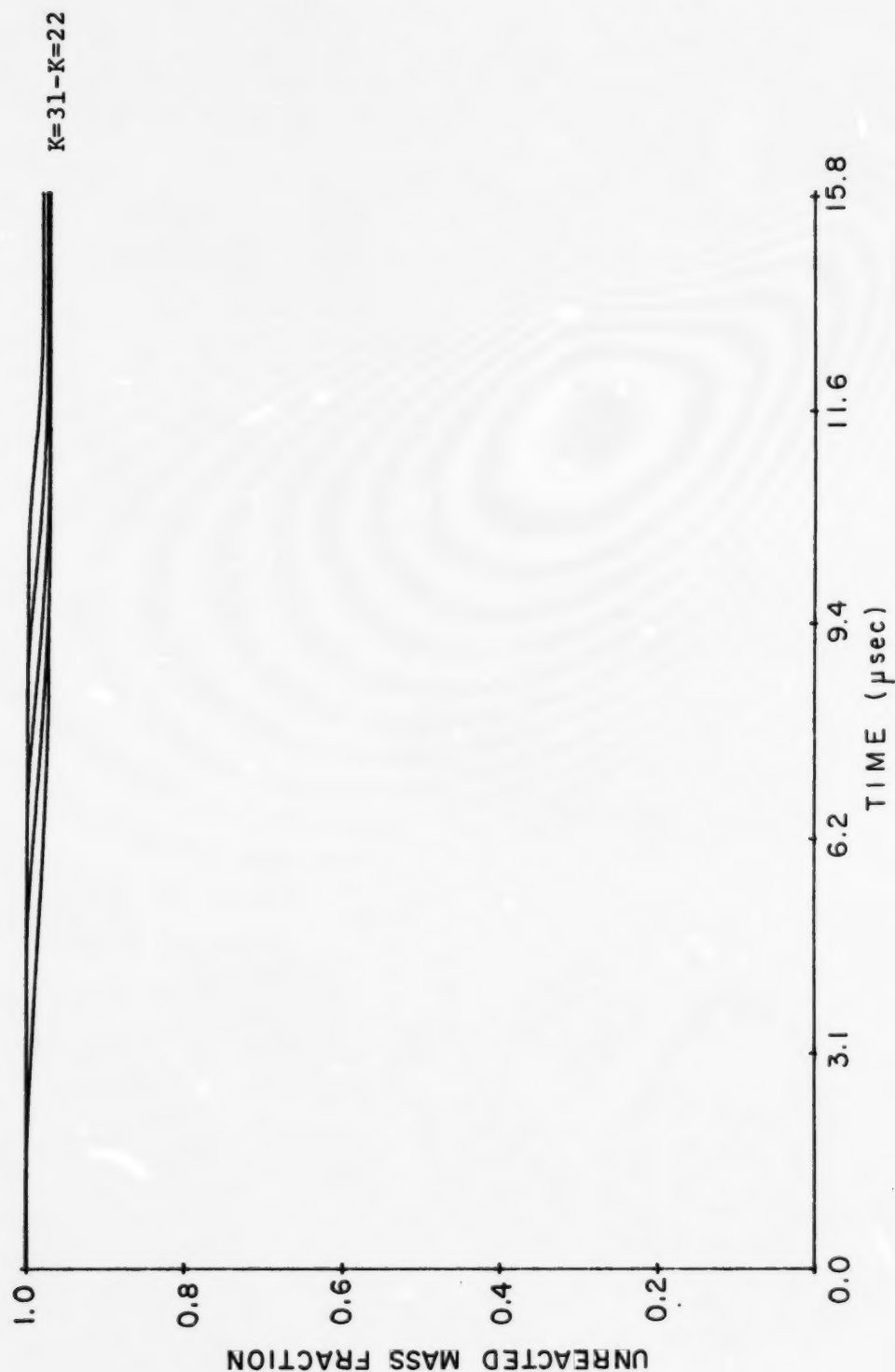


FIGURE 115: MASS FRACTION OF UNREACTED EXPLOSIVE VS. TIME FOR SLURRY B IMPACTED BY A 5.0 cm DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF 300 m/sec.

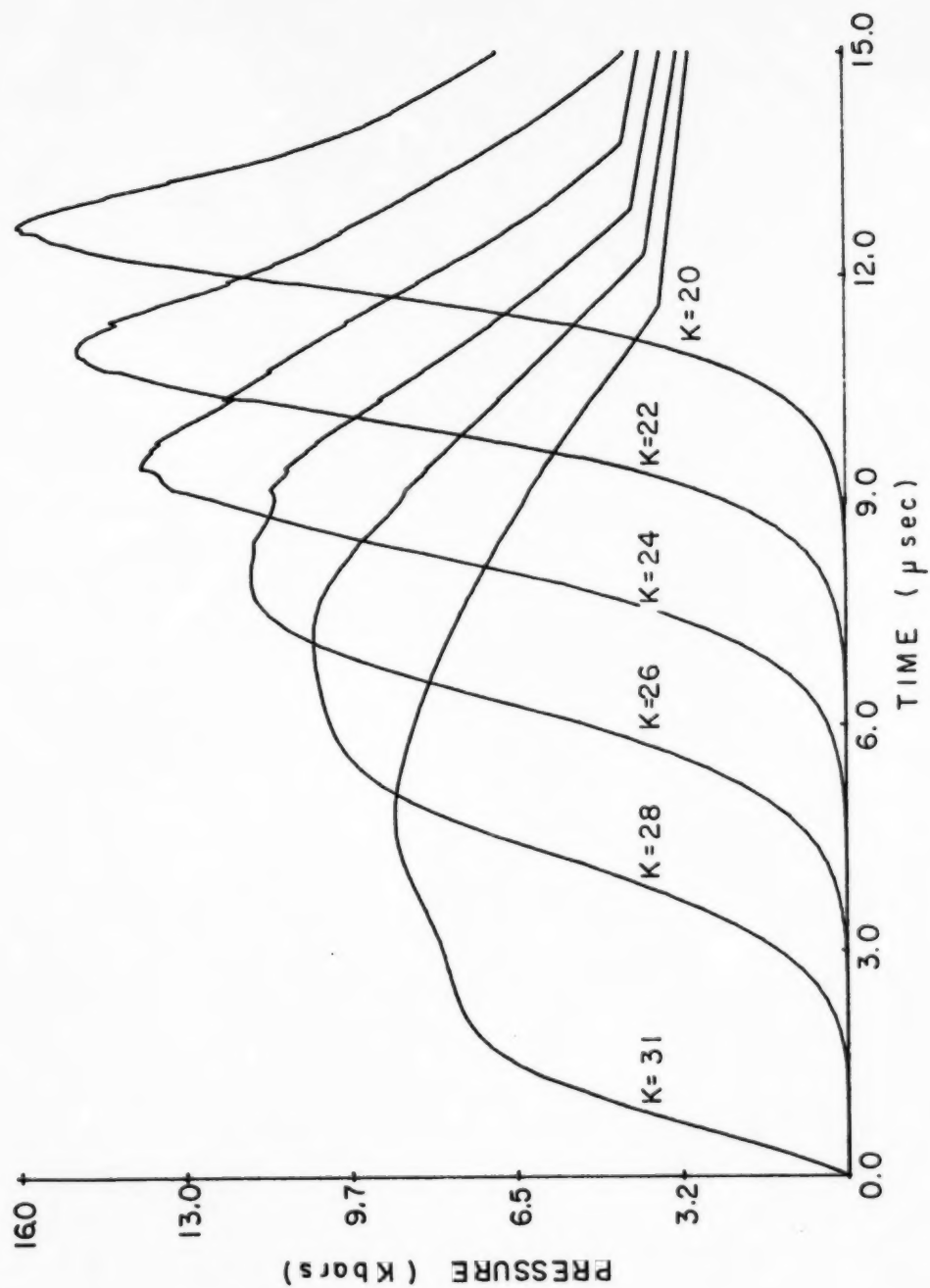


FIGURE 110: PRESSURE-TIME HISTORIES FOR SLURRY B IMPACTED BY A 5.0 CM DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF 350 m/sec.



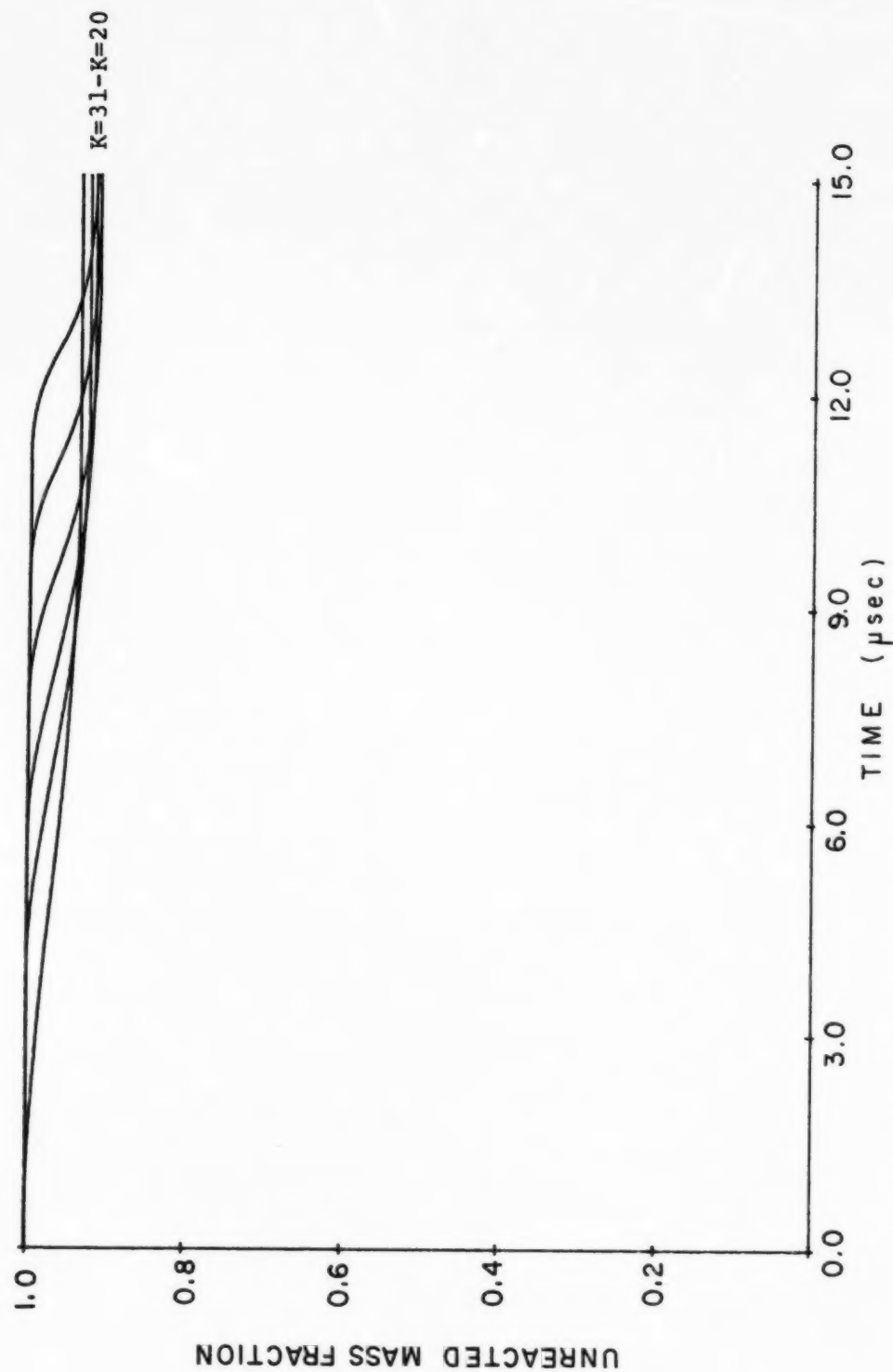


FIGURE 117: MASS FRACTION OF UNREACTED EXPLOSIVE VS. TIME FOR SLURRY B IMPACTED BY A 5.0 cm DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF 350 m/sec.

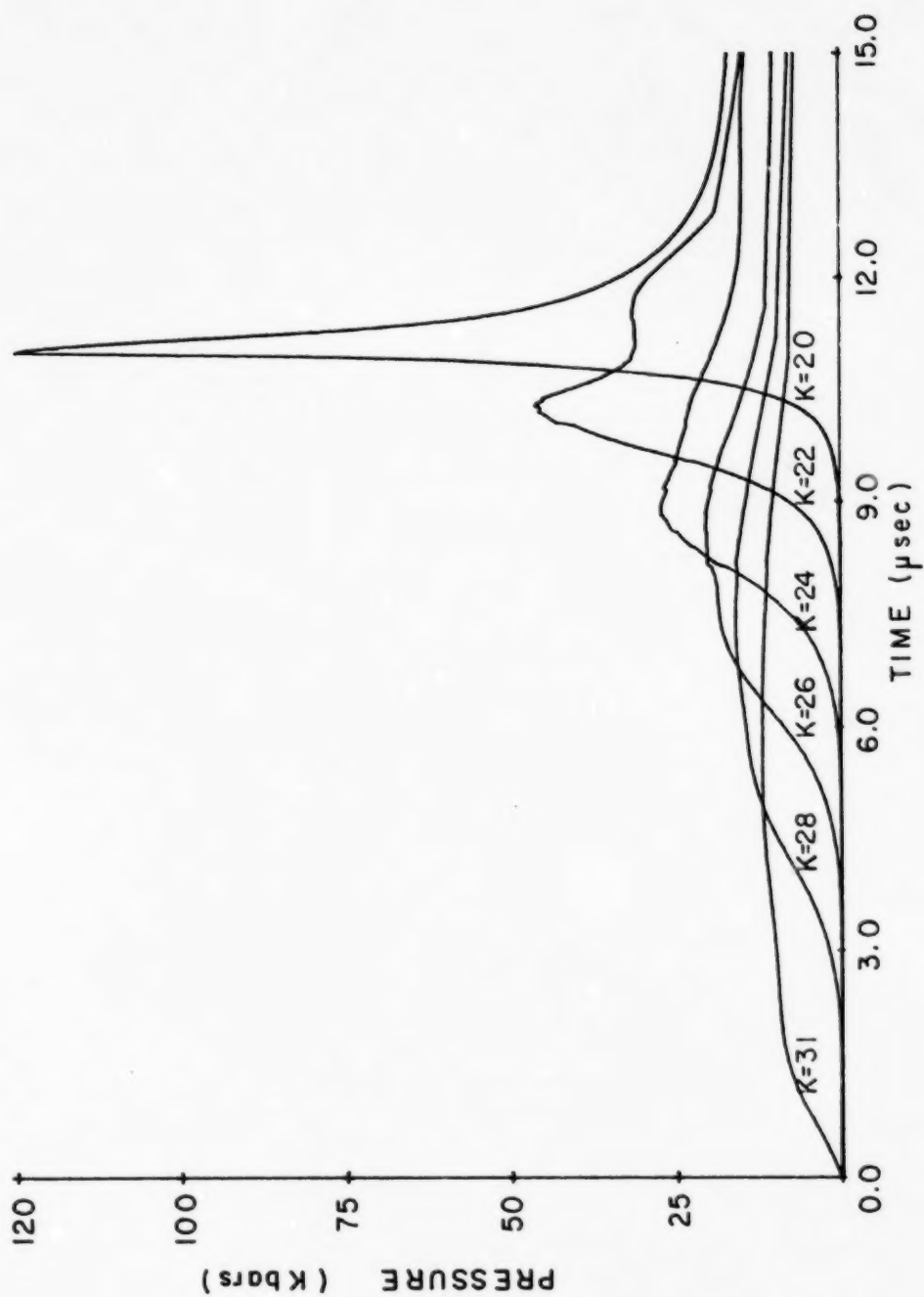


FIGURE 118: PRESSURE-TIME HISTORIES FOR SLUGS IMPACTED BY A 5.0 cm DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF 400 m/sec.

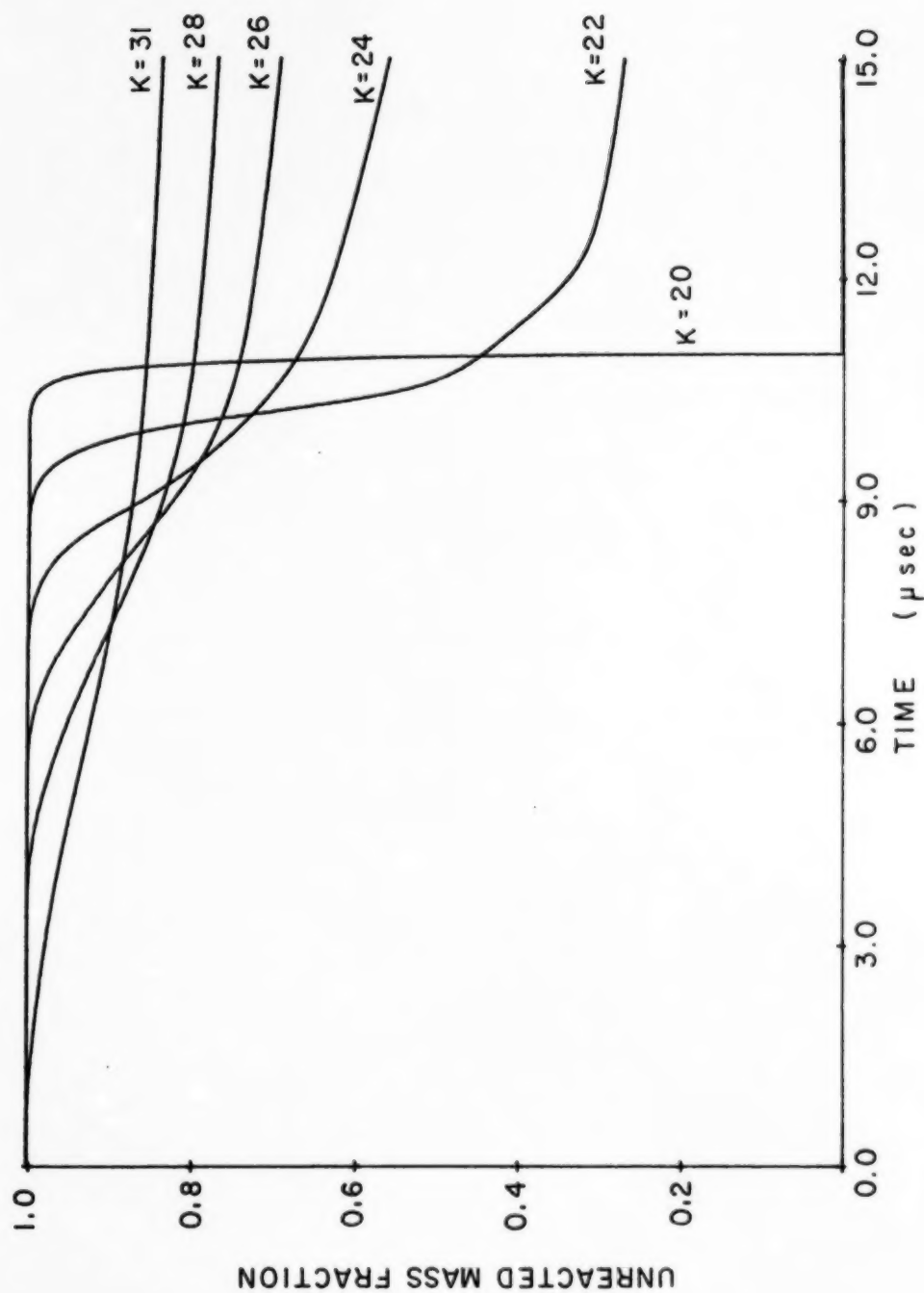


FIGURE 110: MASS FRACTION OF UNREACTED EXPLOSIVE VS. TIME FOR SLURRY B IMPACTED BY A 5.0 cm DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF 400 m/s.

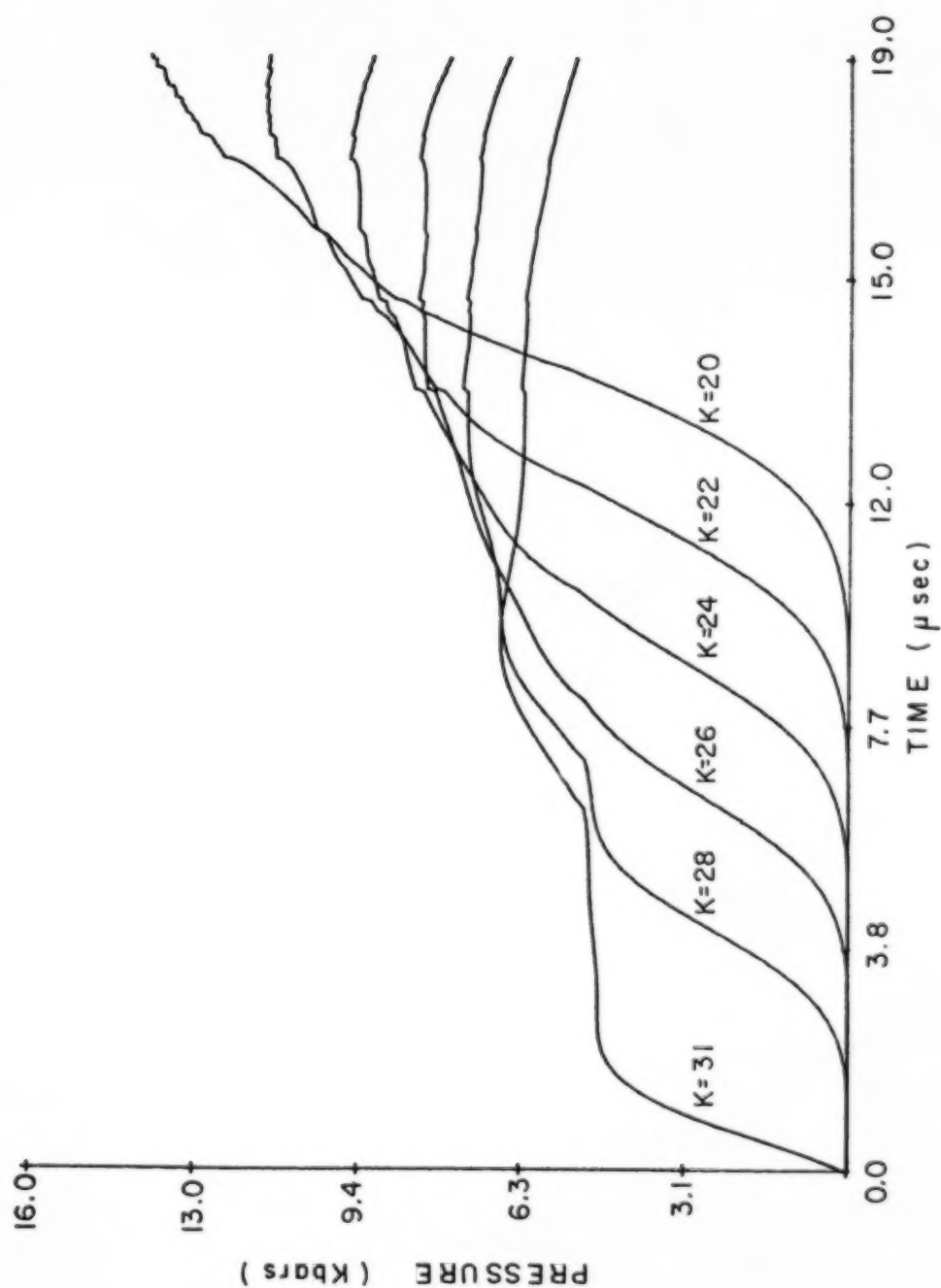


FIGURE 120: PRESSURE-TIME HISTORIES FOR GLASS B IMPACTED BY A 10.0 cm DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF 250 m/sec.

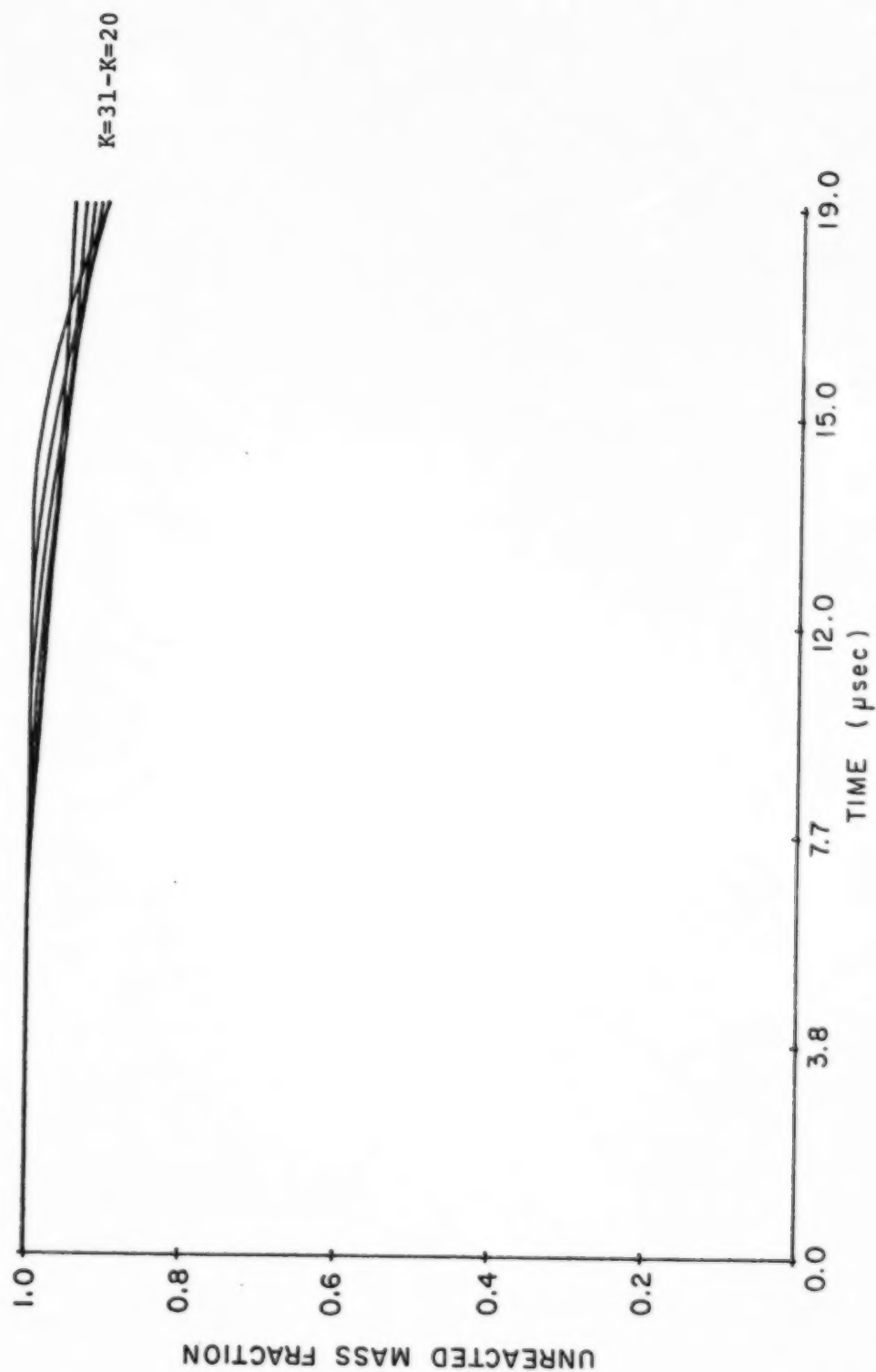


FIGURE 121: MASS FRACTION OF UNREACTED EXPLOSIVE VS. TIME FOR GURNEY B IMPACTED BY A 10.0 cm DIAMETER ALUMINUM PROJECTILE OF A VELOCITY OF 250 m/sec.

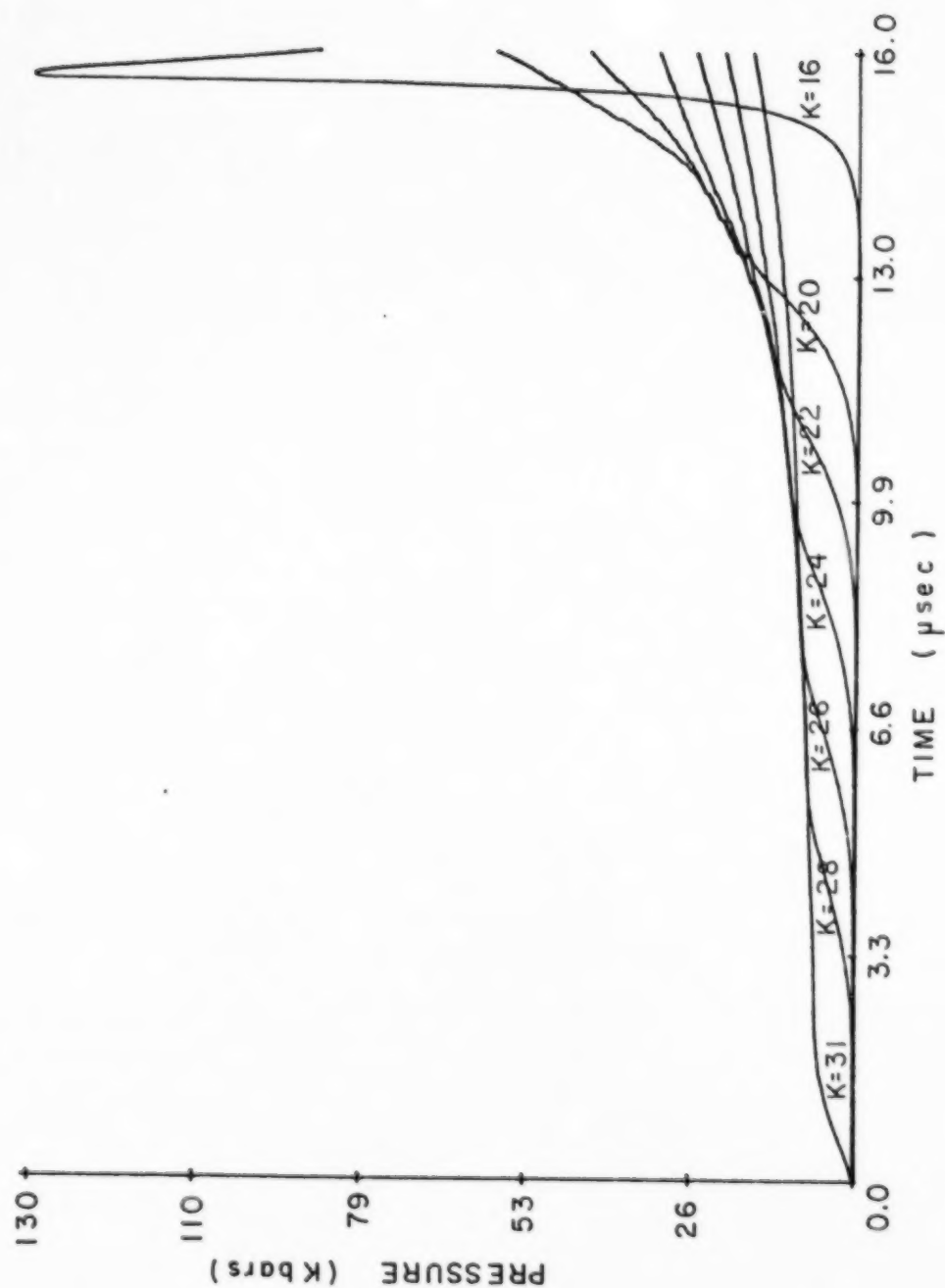


FIGURE 122 PRESSURE TIME HISTORIES FOR GLURRY B IMPACTED BY A 10 cm DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF 300 m/s.

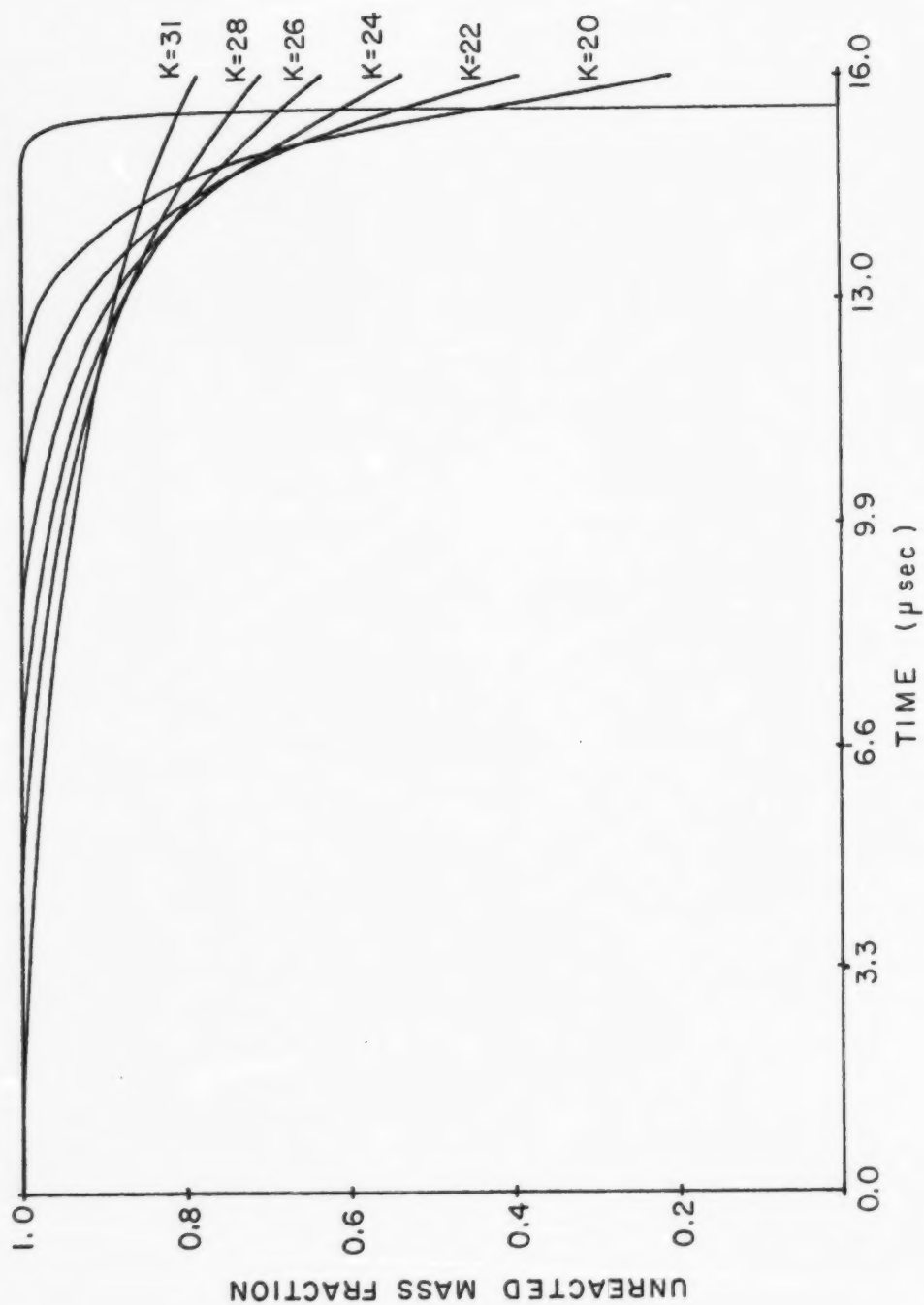


FIGURE 12.3: MASS FRACTION OF UNREACTED EXPLOSIVE VS. TIME FOR SLURRY B IMPACTED BY A 10 cm DIAMETER ALUMINUM PROJECTILE AT A VELOCITY OF 300 m/sec.

TABLE 7.15: CALCULATED AND EXPERIMENTAL RESULTS FOR SLURRY B

| IMPACTOR                                                            | EXPERIMENTAL<br>VELOCITY (m/s)<br>AND RESULT | CALCULATED VELOCITY<br>(m/sec) and RESULT             |
|---------------------------------------------------------------------|----------------------------------------------|-------------------------------------------------------|
| Aluminum<br>Projectile<br>(diameter: 2.5 cm<br>length: 5.0 cm)      | 347 - failed<br>444 - detonated              | 400 - failed<br>500 - marginal                        |
| Aluminum<br>Projectile<br><br>(diameter: 5.0 cm<br>length: 10.0 cm) | 344 - failed<br><br>350 - detonated          | 300 - failed<br><br>350 - marginal<br>400 - detonated |
| Aluminum<br>Projectile<br>(diameter: 10.0 cm<br>length: 13.0 cm)    | 344 - failed<br>350 - detonated              | 250 - marginal<br>300 - detonated                     |



## CHAPTER EIGHT

### 8.0 CONCLUSIONS

From the comparison between experimental and calculated results it follows that the numerical model "HYDREL" reproduced the main characteristics of the initiation of the commercial and military explosives tested. The code predicted the impact initiation with sufficient accuracy. Moreover it demonstrated the dependency of the initiation of the various explosives on the material and geometric properties of the impactor.

It was found that materials of high density (e.g. brass) initiate explosive targets easier than materials of lower density (e.g. aluminum).

The diameter of the projectile was shown to be very important when dealing with small projectiles. This is expected, however, because initiation is influenced by the dimensionality of the experiment. When the diameter is smaller the effect of side rarefactions becomes more obvious. In the calculations, in cases it was observed that when the projectile diameter was small and the impact velocity high, initiation occurred almost immediately on impact. However if the projectile velocity was not high enough, detonation did not propagate but was quenched by the action of following rarefactions.

Flyer plates because of their large area of impact impose a one dimensional impact and initiate the explosives easier. This was demonstrated in the case of ANFO and cast Composition B. Flyer plate data which were obtained for cap sensitive emulsion products demonstrated the same effect for cap sensitive products. These data however were not used in the quantitative comparison because of inaccuracies in the calculation of the plate velocity

caused by possible spalling of the metal plate. In the case of a slowly moving plate spalling is possible due to insufficient thickness of driver explosive behind the plate.

Blasting cap sensitive emulsion and slurry products are similar with regard to their safety at high velocity impacts. However drop weight tests have shown emulsion explosives to be safer. Therefore the drop weight test should not be used as a single criterion to evaluate impact sensitivity of commercial products.

Another interesting result of the investigation of commercial products is that they were found to be more sensitive than cast military explosives such as cast TNT and cast Composition B. Cast TNT and cast Composition B are not cap sensitive though. It appears that there is a close relationship between cap sensitivity and impact sensitivity.

With regards to the modelling code the most important information is the Pop plot. It was found that Pop plot data could be obtained more easily for emulsion than for slurry explosives. Emulsion explosives consist of a more homogeneous mix containing small liquid droplets sustained in a continuous liquid matrix and microscopic microballoons. In slurries the mix is crude containing liquid with large solid objects (prills, pieces of gum etc.) and large voids. These discontinuities can be detrimental in the determination of a Pop plot. Slurry C was a typical example of a product in which the discontinuities produced a very significant scatter of data. It is rather obvious that Pop plot work is recommended for products which contain small size grains and chemical ingredients uniformly distributed inside the mass of the explosive.

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